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DESIGN OF AN OFF-AXIS WIDE FIELD-OF-VIEW VISUAL DISPLAY SYSTEM --ETC(U)
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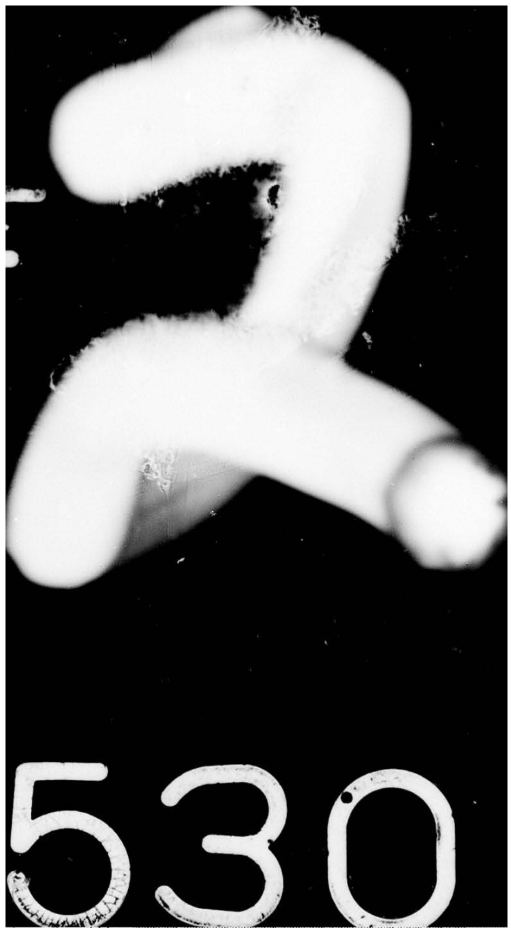
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REPORT NO. NADC-79023-20

LEVEL II

DESIGN OF AN OFF-AXIS WIDE FIELD-OF-VIEW *Visual*
DISPLAY SYSTEM FOR FLIGHT SIMULATORS

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Prepared for
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This report describes the analysis and design of an off-axis wide field-of-view visual display system, including component specifications and structural drawings. A fabrication cost and schedule estimate is also presented.

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SUMMARY

The general objective of this task is to research and design a display system which will present a real world visual image over a 180° horizontal by 60° vertical field-of-view, providing a visual simulation capability of addressing a wide specter of flight mission problems. These visual mission problems will include the landing of a LAMPS (Light Airborne Multi-Purpose System) helicopter on a destroyer and also the problems associated with the takeoff and landing of a V/STOL (Vertical/ Short Take-Off and Landing) aircraft on a naval surface ship.

The first specific objective of this task is to pursue the off-axis visual display design concept presented in the NAVAIRDEVCEN (Naval Air Development Center) report entitled "Study of Wide Field-Of-View Visual Display Systems for Flight Simulators" (reference (a)) and present a finalized design. The finalized design will include component specifications, optical analysis, display component support structure design and a system weight estimate. A second specific objective is to present a fabrication cost and schedule estimate for the NAVAIRDEVCEN Wide Field-Of-View Display finalized design.

Two designs for obtaining the 180° horizontal by 60° vertical field-of-view will be presented in this report. The Phase I off-axis visual display design concept utilizes a single TV (television) projector/ rotating mirror system for producing the required 180° by 60° field-of-view. This design concept is illustrated in Figure 1. The NAVAIRDEVCEN Off-Axis Display system consists of a TV projection system, a rear projection screen, located off-axis from the viewing area, and a large spherical mirror which presents a virtual image, appearing at infinity, to the viewer. The rotating mirror system is used to translate the real world image throughout the 180° horizontal field-of-view in 60° segments. This design concept provides a 40° downward view, required for helicopter and V/STOL landing missions, and also provides a large exit pupil dia

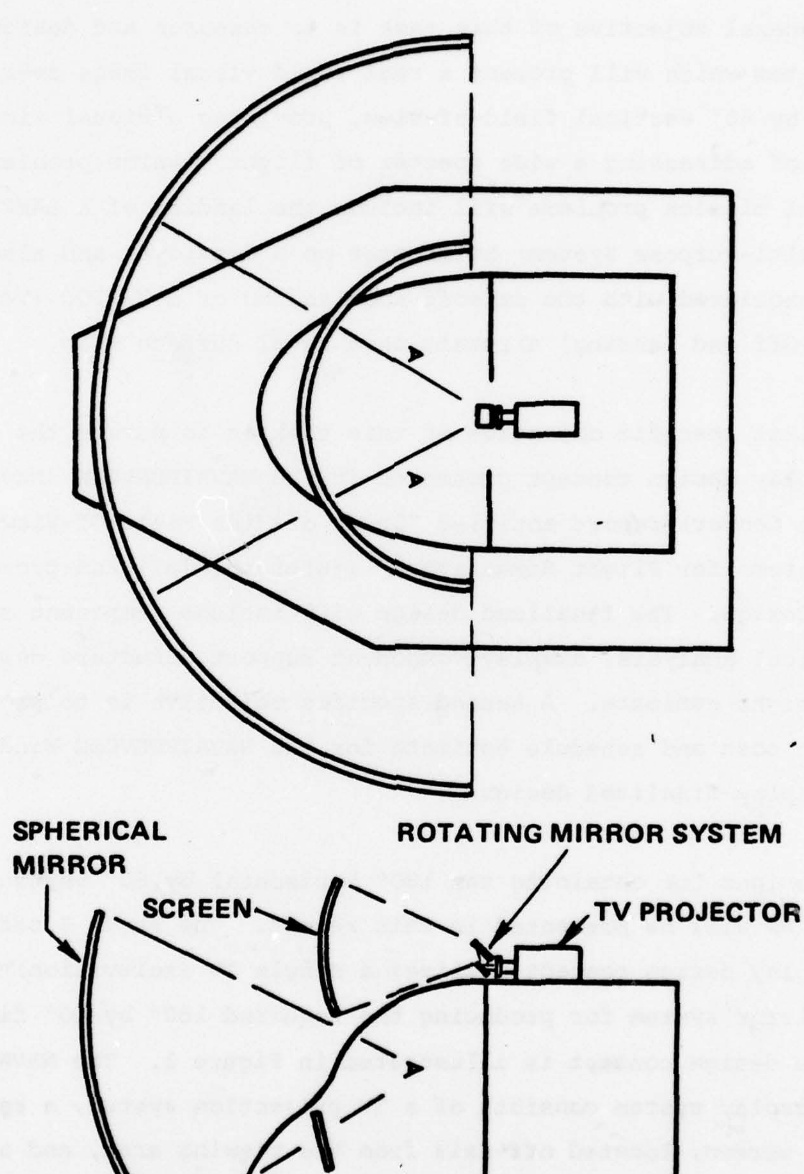

Figure 1. NAVAIRDEVCEN Wide Field-of-View Visual Display Phase I Design Concept

for a side-by-side cockpit configuration. The Phase II design concept consists of a three TV projector/stationary folding optics mirror system for producing a continuous 180° horizontal by 60° vertical display presentation. This design concept is illustrated in Figure 2. A Phase I design can be converted into a Phase II design with a minimimal effort, or the Phase II design can be fabricated directly, bypassing the Phase I design concept.

The NAVAIRDEVCEN Off-Axis Wide Field-Of-View visual display system concept is superior to other visual display system designs in the capability of presenting a real world virtual image, appearing at infinity, throughout a large viewing volume width (48 inches). The Navy's LAMPS helicopter and proposed V/STOL aircraft utilize side-by-side cockpit configurations, requiring this large viewing volume width. This display system concept is also ideally suited for producing large downviews.

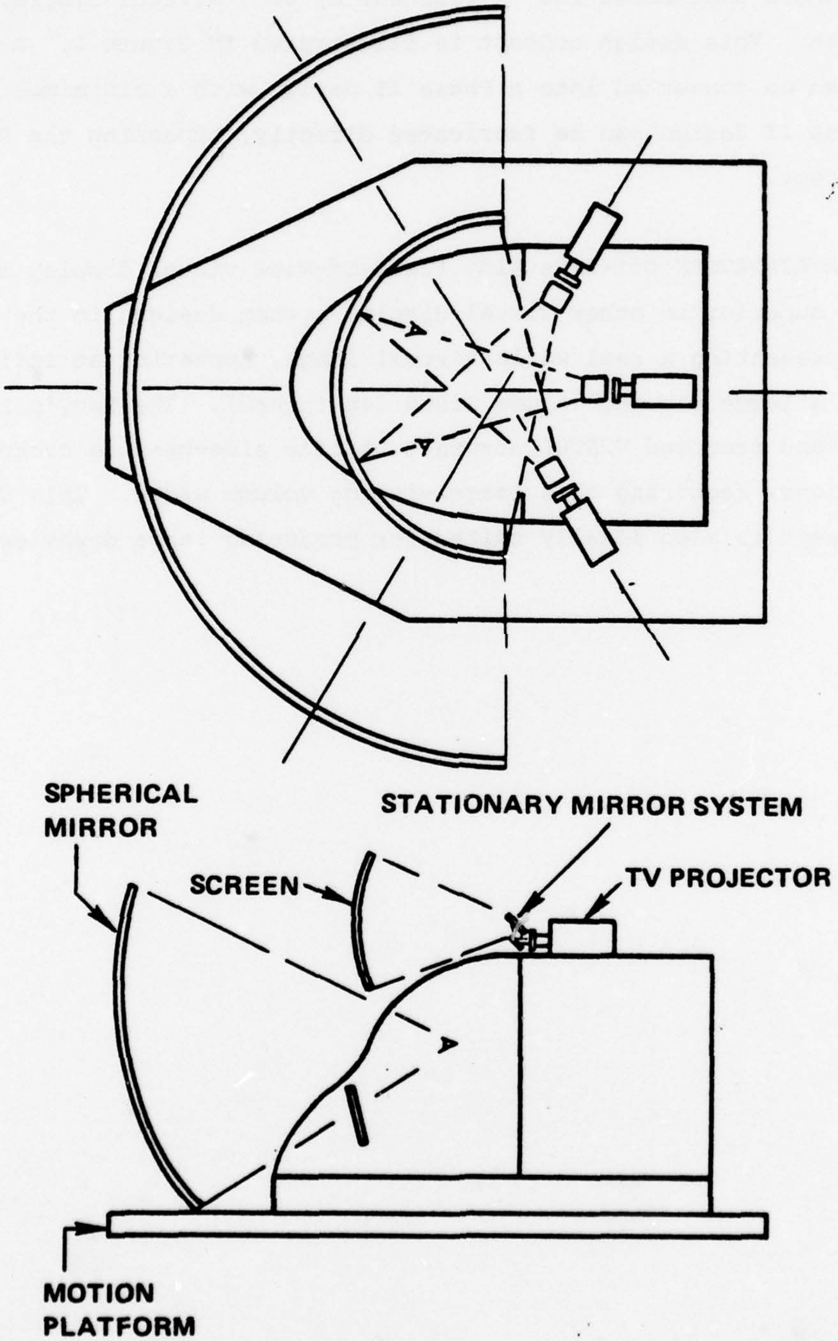

Figure 2. NAVAIRDEVCEN Wide Field-of-View Visual Display
Phase II Design Concept

RESULTS

The NAVAIRDEVCEN Off-Axis Visual Display design concept was analyzed by the General Electric Company under contract number N62269-78-C-0170. The results of this contract provided exact dimensions for components, and distances between components. The results are detailed in Figure 3 for the single TV projector/rotating mirror design concept and in Figure 4 for the three TV projector/full 180° horizontal display image design concept.

The finalized NAVAIRDEVCEN Wide Field-Of-View Visual Display System consists of the following major components.

1. A 14 ft radius spherical mirror consisting of 14 trapezoidal segments, utilizing a cast epoxy on a rigid honeycomb aluminum preform manufacturing process.

2. A toroidal shaped rear projection screen (78.2 inch radius by 101.3 radius) consisting of seven trapezoidal segments utilizing an acrylic material with a fresnel prism bonded layer manufacturing process.

3. The General Electric Company's PJ5150 Light Valve Projector, which provides 1023 TV lines, with an output brightness of 500 lumens. The Phase I design utilizes a single TV projector while the Phase II design utilizes three TV projectors.

4. A Phase I design rotating mirror system consists of a 5 ft by 4 ft rotating mirror and a 3 ft by 2 ft stationary mirror. The rotating mirror is driven at the rate of 60° in about 1/2 sec by a servo system, consisting of a 1/2 hp motor/3 turn potentiometer/amplifier combination. Optical predistortion is incorporated into the 5 ft by 4 ft mirror.

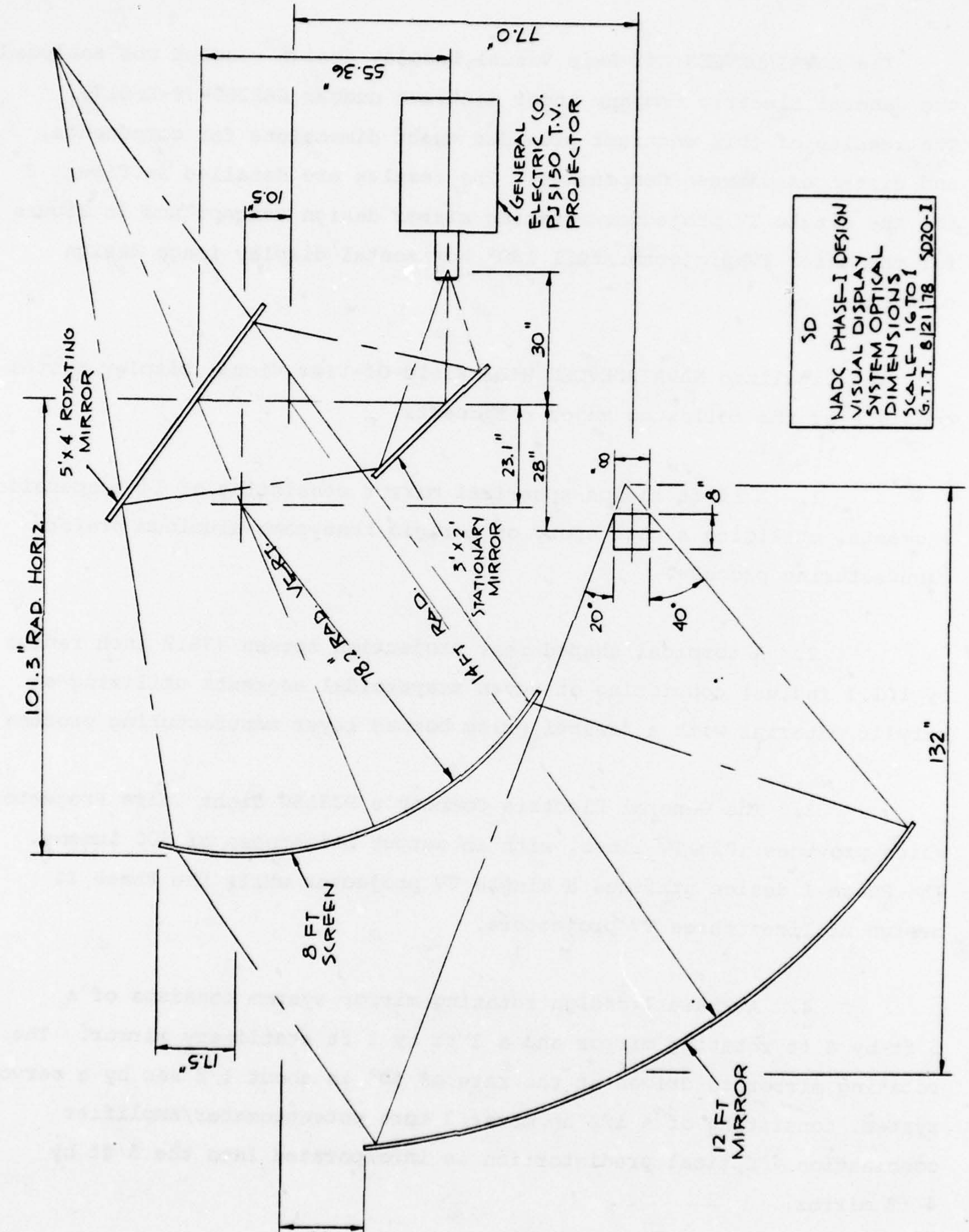

Figure 3. NAVAIRDEVCEN Visual Display Optical Analysis (Design Phase I)

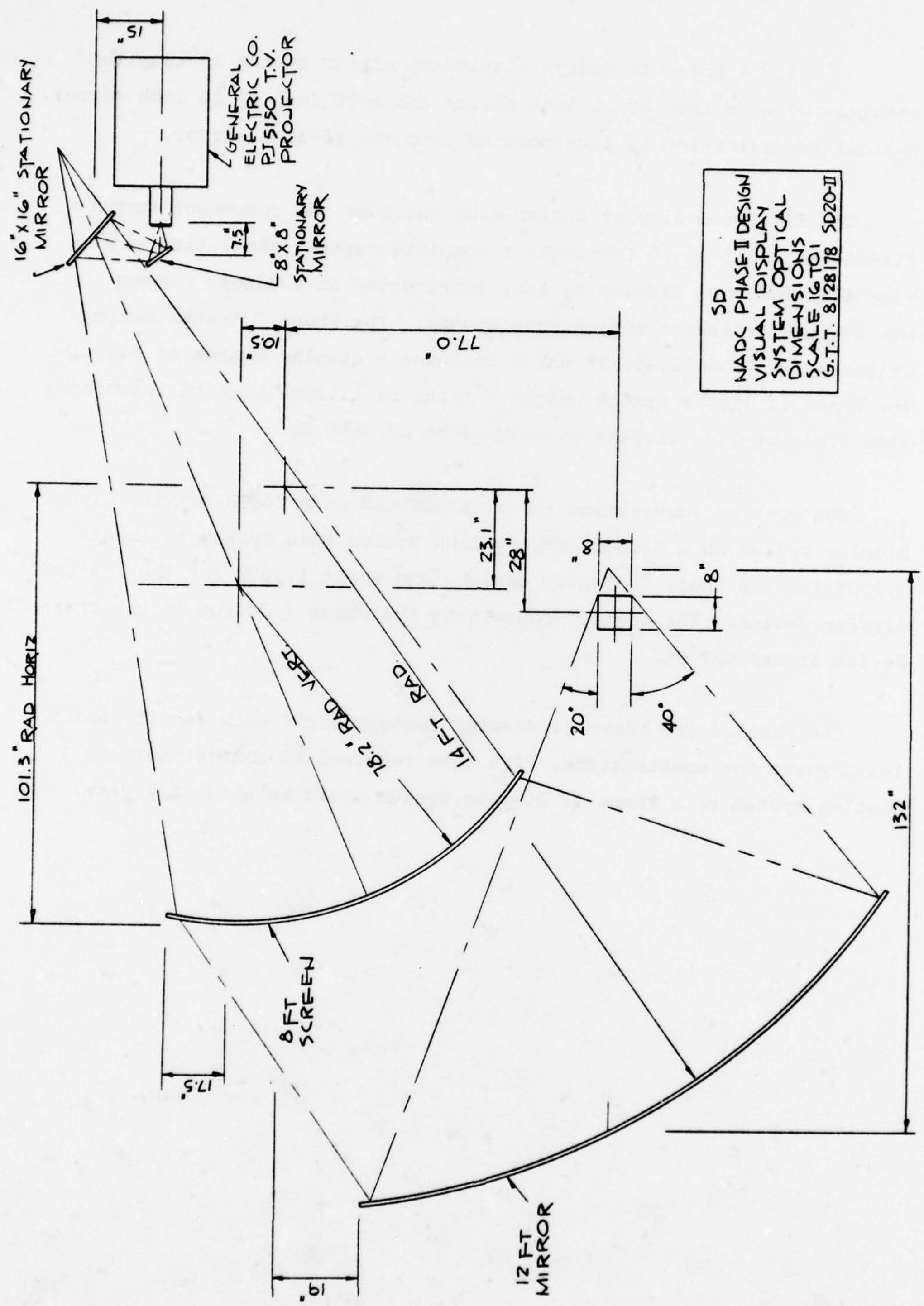

Figure 4. NAVAIRDEVCEN Visual Display Optical Analysis (Design Phase II)

5. A Phase II design stationary mirror system (3 required) consists of an 8 inch by 10 inch mirror and a 16 inch by 16 inch mirror. Optical predistortion is incorporated into the 16 inch mirror.

The finalized display design also includes the component support structures required to fabricate a complete cockpit simulation with a wide field-of-view display system, constructed on a Singer Company six degree-of-freedom motion base system. The Phase I system design weighs a total of 11,256 lb which includes a display system of 5456 lb. The Phase II system design weighs a total of 11,598 lb which includes a wide field-of-view display system weight of 5800 lb.

The cost of fabricating the NAVAIRDEVCEN Wide Field-Of-View Visual Display system on a Singer Company Link Motion Base System is about 1,100K for the Phase I display design, and about 1,250K for the Phase II display design. The cost of converting the Phase I design to the Phase II design is about 200K.

The Phase I and Phase II display designs would each require about 1-1/2 years for construction. The time required to convert a Phase I display system to a Phase II display system would be about 1/2 year.

CONTENTS

FIGURES

TABLES

1.0 Task I - Visual Simulation Display Analysis and Basic Design

The major parameters which make up the requirements of a wide field-of-view visual display system include field-of-view, resolution, brightness, contrast, exit pupil diameter, and picture color. These parameters were fully described in reference (a). In addition to these parameters, the following technical design considerations must be addressed:

- Viewing volume
- Geometric distortion
- Collimation error
- Image registration
- Mapping

Each of these design considerations will be discussed in the next section of this report.

1.1 Design Analysis

1.1.1 Viewing Volume

The viewing volume width for a side-by-side cockpit configuration is equal to the distance between the pilot and copilot plus a reasonable dimension to allow for some head movement. Allowing for 36 inches between pilot and copilot and a head movement dimension of ± 4 inches in the forward and vertical directions and ± 6 inches in the lateral direction would produce a viewing volume of 48 inches (lateral) by 8 inches (forward/aft) by 8 inches (vertical).

For the off-axis display design, as the viewing volume approaches the center of the spherical mirror, the display imagery is improved. This distance, however, can only be reduced to the point where interference between the line of sight and the physical screen occurs. The center of the viewing volume for the NAVAIRDEVCEN Off-Axis Visual

Display system, as determined through optical analysis, is 77 inches from the center of the spherical mirror.

1.1.2 Geometric Distortion

Spherical aberration, coma, and astigmatism refer to the failure of a lens to form a point image of a point object. Distortion is an abberration arising not from lack of sharpness of the image, but from the variation of magnification with distance from the axis. If the magnification increases with increasing distance, the outer parts of the field are disproportionately magnified. This effect, illustrated in Figure 5, is referred to as pin cushion distortion. If magnification decreases with increasing distance, the opposite effect, known as barrel distortion, is obtained. This effect is illustrated in Figure 6. The characteristic or systems ability to transfer straight line images from input to observer is of great importance when considering:

(a) Approaches to runways where straight lines are very much in evidence.

(b) Acceptability of an external world where the straight horizon is used as a flight reference.

The primary contribution of image distortion for an off-axis display system is illustrated by the ray trace in Figure 7. As the eye position moves off-axis (Point A to B), the optimum focal surface changes location and shape, which affects a change in magnification and image location.

For the NAVAIRDEVCEN Off-Axis Display System, distortion values less than 5% are a design goal. The display distortion characteristic known as "swimming distortion" is defined as the effect caused by the differences in relative directions to various portions of the field-of-view as the eye moves throughout the viewing volume. The viewed objects, in effect, take on different localized magnifications in various directions

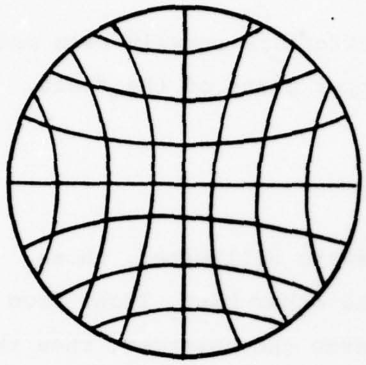

Figure 5. Pin Cushion Distortion

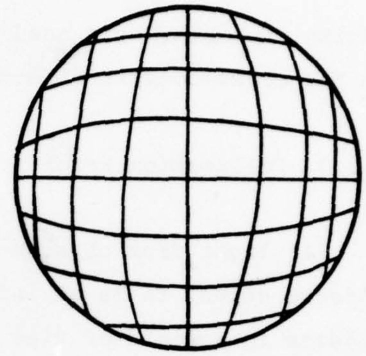

Figure 6. Barrel Distortion

Figure 7. Off-Axis Display Image Distortion Ray Trace

during the observer's head movement. This effect is usually seen mainly in the cross-cockpit direction and in the upper parts of the field.

1.1.3 Collimation Error

If light from objects in a field of view is collimated, those objects appear to be at infinity. If, on the other hand, light from objects in a field of view is divergent towards the observer, then those objects appear to be closer than infinity. If light from objects in a field of view appears to be convergent toward the observer, those objects appear to be farther than infinity or behind the observer. A display system will usually present objects at varying distances between the observer and infinity so that the degree of collimation will vary from divergence towards the observer to true collimation. The degree of collimation determines the excellence of the system.

A third collimation defect known as dipvergence is characterized by a vertical angular deviation between the rays that strike the left and right eyes.

Figure 8 illustrates dipvergence as it would be seen by both eyes alternately, while Figure 9 illustrates dipvergence when the object is viewed by both eyes.

The Optical Design Handbook, MIL-HDBK-141, reference (g), presents an allowable tolerance of 17 arc minutes for convergence, divergence and dipvergence collimation errors.

1.1.4 Image Registration

A 1° or less discontinuity in the field is to be expected as a criterion in a display that is ideally intended to be continuous. This criterion will only apply to the Phase II design, since this design utilizes three 60° by 60° field-of-view images to provide for a continuous

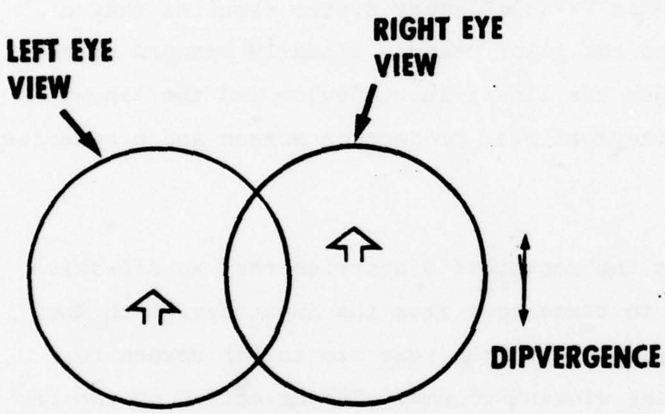

Figure 8.

Dipvergence (Single Eye View)

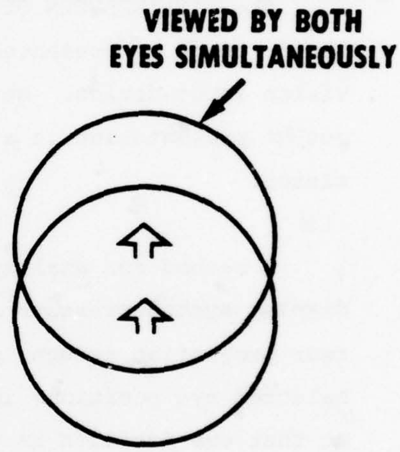

Figure 9.

Dipvergence (Both Eyes View)

180° field-of-view. A square aperture provided in the TV projector lens adapter will provide a clear sharp edge at the intersection of adjacent images. Ample optical alignment adjustments in the TV projector/folding mirror assembly will provide a means of aligning the adjacent images within the allowable discontinuity tolerances.

1.1.5 Mapping

The NAVAIRDEVCEN Off-Axis Visual Display System requires that a linear image be presented to the pilot using a linearly scanned television input device. Between the linear input device and the linear output presentation is a spherical rear projection screen and a spherical mirror.

A method for analyzing the amount of distortion that an off-axis display system presents is to trace rays from the input device to the rear projection screen, and then from the rear projection screen to selected eye positions in the viewing volume. The direction of the ray at that eye position is compared with the correct direction for evaluation of distortion. The results of the ray trace can be presented on a distortion mapping plot, which compares an ideal grid pattern with the geometric distortions obtained from the ray trace. The mapping plots for the NAVAIRDEVCEN Phase I and Phase II Visual Display System design are presented in Appendix A.

One method for correcting geometric distortion employs adjustment of the surface contour of one of the television projector folding mirrors to provide necessary predistortion to the rear projection screen image. Predistortion can also be inserted into the shape of the television scan lines or in the CGI (Computer Generated Image) system if this type of Scene Generation is utilized.

1.2 NAVAIRDEVCEN Wide Field-Of-View Visual Display Requirements

The NAVAIRDEVCEN requirements for the design of a wide field-of-view visual display system are listed in Table 1. It should be noted that the 40° downward field-of-view requirement is a change from the 30° value presented in reference (a). This change was a result of several visual display system discussions with the General Electric Company during the execution of the display systems optical analysis contract. This change was determined to be feasible and a definite improvement in the display systems mission requirements.

1.3 NAVAIRDEVCEN Visual Display Basic Design

The NAVAIRDEVCEN Wide Field-Of-View Visual Display system design concept, described in the summary of this report, was analyzed so that a more detailed basic design could be presented. The Phase I design concept, illustrated in Figure 1, utilizes a single TV projector/rotating mirror system to produce the 180° horizontal by 60° vertical display image. Presently, the NAVAIRDEVCEN is building a terrain model scene generator system which utilizes an optical probe with a 60° by 60° field-of-view. This terrain model system therefore can be used to present a 60° by 60° image on the visual display system. The TV projector/rotating mirror system would allow the 60° by 60° segment to be translated throughout the entire 180° display field-of-view. The NAVAIRDEVCEN optical probe has a rhomb prism system, which is rotatable about the azimuth axis to produce azimuth angular line-of-sight motion so that the 180° field-of-view can be scanned on the terrain model in 60° by 60° segments. The field-of-view of interest could be selected by the pilot. This could be accomplished with a switch on the cockpit stick control or with a head movement sensor system on the pilot's helmet.

The Phase II design concept utilizes a three TV projector/stationary folding optics mirror system to provide a continuous 180° horizontal by 60° vertical field-of-view. This design concept is illustrated in

TABLE 1. NAVAIRDEVCEN WIDE FIELD-OF-VIEW VISUAL DISPLAY REQUIREMENTS

Field-of-view	180° horizontal; 60° vertical with a 40° downward view
Resolution	5 arc min
Brightness	5 ft lamberts
Contrast	20 to 1
Exit pupil diameter	4 ft (min)
Eye relief	4 ft (min)
Picture color	Chromatic
Motion system	Compatible with visual systems size and weight
Scene generator system	Terrain model and computer generated images
Mission requirements	Takeoff and landing, weapon delivery, target identification and acquisition
Cockpit configuration	Side-by-side or single seat
Aircraft	V/STOL, helicopter or fixed wing
Viewing volume	4 ft (lateral) by 8 in. (forward) by 8 in. (vertical)
Distortion	Less than 5%
Collimation error	±17-arc minutes of convergence, divergence and dipvergence as specified in Mil HDBK-141
Image registration	Image discontinuity less than 1°

Figure 2. The display system will be utilized with a computer generated image scene generator system or with the purchase of a terrain model optical probe, which would produce a picture over a 180° field-of-view. The 180° field-of-view optical probe is not yet within the state-of-the-art. Computer generated image systems presently cost about 3 million dollars. The Phase II design will require an image registration tolerance of the three 60° by 60° pictures to be less than 1°.

In addition to the NAVAIRDEVCEN Wide Field-Of-View Visual Display Requirements, Table 1, other design criteria must be presented to reduce the number of design variables.

The NAVAIRDEVCEN Off-Axis Display system design, described in this report, will utilize a spherical shaped mirror configuration. Several mirror shapes, including spherical, ellipsoidal, parabolordal and double spherical, were investigated and described in references (b) and (c). It was determined in these reports that the spherical shape was the most practical mirror shape to manufacture and was competitive with the other mirror shapes in optical properties.

The rear projection screen will have a toroidal shape. A toroid is a spherical shape with the vertical diameter being greater or less than the horizontal diameter. The vertical contour of the screen will be described by a spherical locus of points determined by an optical ray trace investigation of the viewing volume, the spherical mirror and the theoretical rear projection screen plane. The horizontal contour of the screen will be spherical also, and will utilize the same center point as the spherical mirror. The toroidal shaped rear projection screen was determined to have the better optical characteristics according to references (b) and (c).

The TV projection system, described later in this report, will be the General Electric Company's color light valve projection system. The Phase I and Phase II basic designs use a modified General Electric 2X

lens adapter, with the light valve projector, which produces an 8 ft wide picture with a projector to screen dimension of about 12 ft. The horizontal angular coverage of this optical system is about 37°. The light valve projection system presents a picture with a 3 to 4 aspect ratio; therefore, the picture height for an 8 ft wide picture is 6 ft. The 2X lens adapter aperture must be modified to produce a square picture.

The Singer Company Link 48 or Link 60 synergistic Six-Degree-of-Freedom Motion System, as described in reference (d), will be utilized as the motion system for the NAVAIRDEVCEN Wide Field-Of-View Display System. This motion system allows for a total flight simulator payload of 18,000 lb.

A basic design was generated utilizing the design criteria discussed in the previous paragraphs. The basic design layout, illustrated in Figure 10, presents approximate dimensions for components and distances between components. This drawing was used as the basic design drawing for an off-axis visual display optical analysis investigation. This contract work produced by the General Electric Company, Daytona Beach, Florida, will be discussed in the next section of this report.

It is again worth noting that this basic design included a vertical downward view of 30° and a forward/aft and vertical viewing volume of 12 inches. The changes in these values will be discussed in the next section of this report.

1.4 NAVAIRDEVCEN Display Optical Analysis Contract

The basic task of the optical analysis contract was to analyze the NAVAIRDEVCEN visual display basic design, as illustrated in Figure 10, and determine the exact sizes of components and the exact distances between components. A second task was to provide information on the spherical mirror, rear projection screen, TV projector and folding

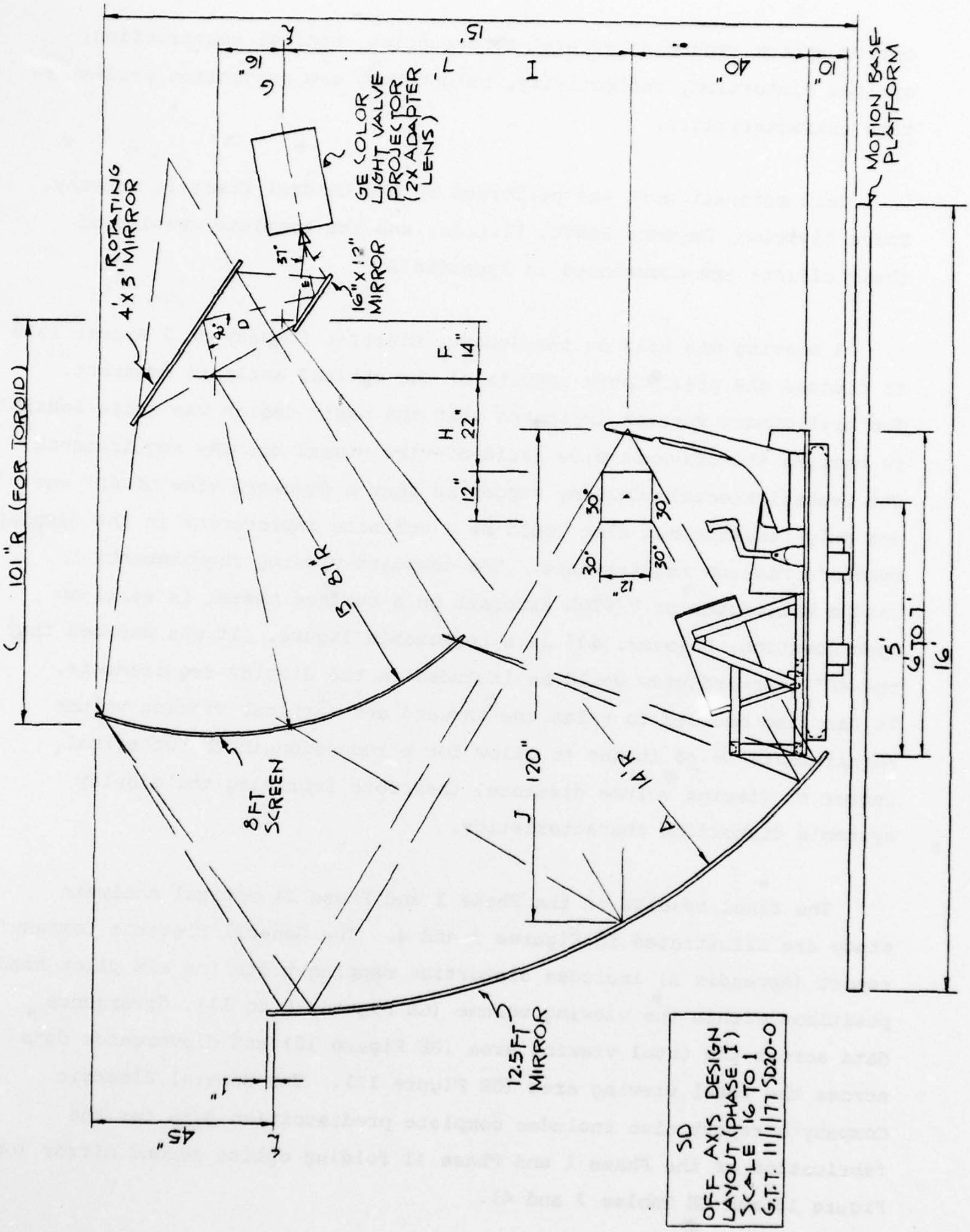

Figure 10. NAVAIRDEVCEN Wide Field-of-View Visual Display Basic Design (Design Phase I)

optics system regarding general construction, optical construction, optical distortion, reflectivity, brightness, and projection predistortion characteristics.

This contract work was performed by the General Electric Company, Space Division, Daytona Beach, Florida, and the complete results of their efforts are documented in Appendix A.

A meeting was held at the General Electric Company on 2 August 1978 to discuss the preliminary results of the optical analysis contract. The preliminary results indicated that the basic design was quite feasible in meeting the off-axis wide field-of-view visual display requirements. The General Electric Company suggested that a downward view of 40° was not only feasible but also would be a definite improvement in the display system's mission requirements. The downward viewing requirements to land a helicopter or V/STOL aircraft on a surface vessel is still an open question; however, 40° is a reasonable figure. It was decided that the 40° downward view would be included in the display requirements. It was also decided to relax the forward and vertical viewing volume requirements to ± 4 inches to allow for a reduction in the spherical center to viewing volume distance, therefore improving the display system's distortion characteristics.

The final results of the Phase I and Phase II optical analysis study are illustrated in Figures 3 and 4. The General Electric Company's report (Appendix A) includes distortion mapping plots for six pilot head positions within the viewing volume (GE Figures 6 to 11), divergence data across the total viewing area (GE Figure 12) and dipvergence data across the total viewing area (GE Figure 13). The General Electric Company's report also includes complete predistortion data for the fabrication of the Phase I and Phase II folding optics second mirror (GE Figure 15 and GE Tables 3 and 4).

The General Electric optical analysis report is printed in its entirety in Appendix A; however, it should be noted that there are some minor disagreements with the information presented in this report. These areas generally are concerned with the fabrication of the spherical mirror and rear projection screen.

2.0 Task II - Visual Simulation Display Component Specifications

The NAVAIRDEVCEN Off-Axis Visual Display system's critical electro-optical subsystems include the spherical mirror, rear projection screen, TV projector system and a folding mirror system, which includes a rotating mirror system for the Phase I design and a stationary mirror system for the Phase II design. This section of the report will discuss each of these subsystems including methods of manufacture, specifications, cost and possible supplier.

2.1 Spherical Mirror

The NAVAIRDEVCEN Off-Axis Wide Field-Of-View Display system will utilize a spherical shaped mirror configuration with a radius of 14 ft. A 180° horizontal by 60° vertical field-of-view, with a 40° downward view, will require a spherical mirror size of 12 ft in height and a trapezoidal width of about 43.7 ft at the top and about 23.6 ft at the bottom. A mosaicing of mirror segments will be used to obtain the required size.

Four different processes that might be used for manufacturing the large concave spherical mirror are described in detail in reference (b). One of the four mirror manufacturing methods (Talbert Reflectors) uses cast epoxy on a rigid honeycomb aluminum preform. Another method employs electroforming or the production of an electro-deposited nickel shell on a master surface. A third method (Liberty Mirror) slumps glass to shape, attaches it to a rigid aluminum preform, and optically grinds and polishes the surface. Finally, a fourth method (Applied Products) utilizes a complete plastic construction. The mirror segments are ground and polished acrylic with a backing of ribbing of the same material. The polished surface is aluminized with a relatively durable coating.

The electroformed manufactured mirror, usually made in 40-inch wide hexagon segments, would require too many segments to make a mirror of the size required for the NAVAIRDEVCEN Off-Axis Display system. The mirror manufacturing processes using glass or plastic would weigh too much to be practical in the NAVAIRDEVCEN display design.

The Talbert Reflector mirror design appears to be the most practical design for the NAVAIRDEVCEN Display system. The Talbert Reflector mirror is formed by applying a separating layer, an epoxy layer, an aluminum honeycomb core, and a final epoxy and fiberglass backing to a master convex spherical mold. A complete description of the manufacturing process is detailed in reference (i).

An example of a sample flight simulator mirror is shown in Figure 11. The sample mirror has a spherical radius of 50 inches and is 26 inches by 41 inches in size. An earlier development effort by Talbert Reflectors yielded a 6 ft by 11 ft reflector with an off-axis ellipsoidal shape weighing about 200 lb. The spherical mirror design utilized in the NAVAIRDEVCEN Wide Field-Of-View Display System will consist of 14 mirror segments, each segment having a trapizoidal perimeter. The general dimensions for the seven top and seven bottom segments are illustrated in Figure 12. Each top segment weighs about 120 lb, while each bottom segment weighs about 80 lb. The total weight of the spherical mirror is about 1400 lb. The estimated cost of producing the spherical mirror, based on a $1350 per sq ft cost of fabricating the molds and a $550 per sq ft cost of fabricating 14 mirror segments, is about $450,000. The specifications for the Talbert spherical mirror are summarized in Table 2.

2.2 TV Projector

The NAVAIRDEVCEN Visual Display system is designed so that one TV projector will cover a 60° by 60° field-of-view. The display requirements detail a resolution of 5 arc min, a brightness of 5 ft lambert,

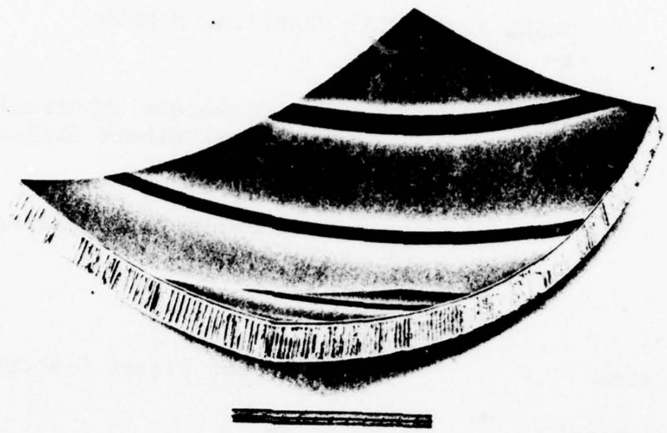

Figure 11. Spherical Mirror Sample

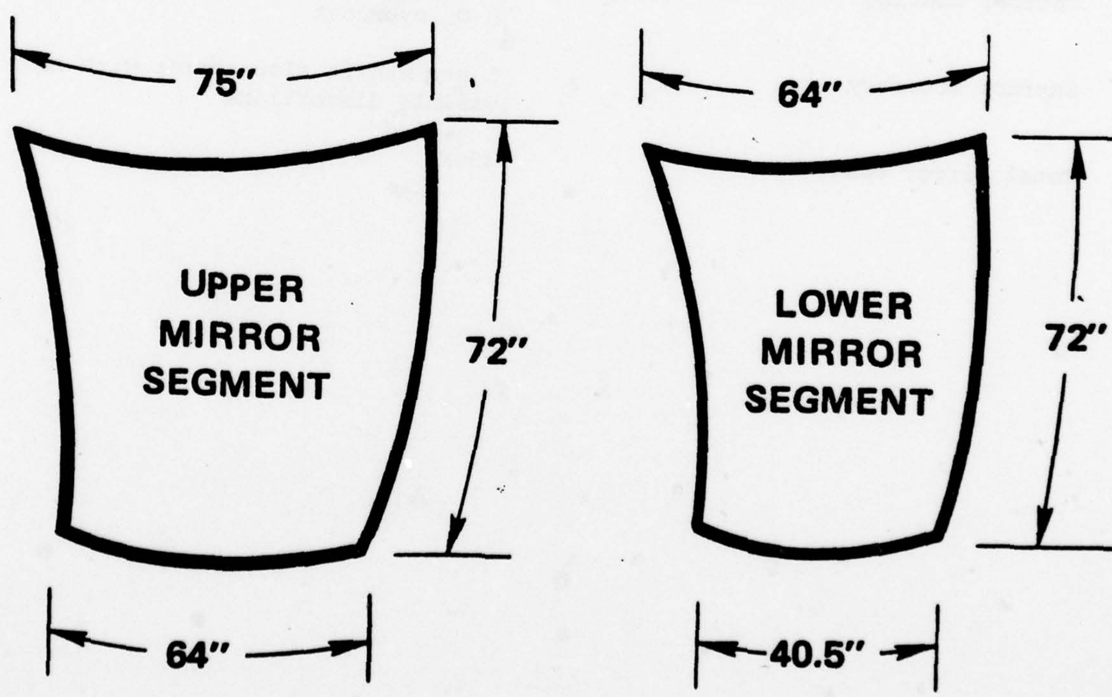

Figure 12. Spherical Mirror Upper and Lower Segment Dimensions

TABLE 2. DISPLAY SPHERICAL MIRROR

Mirror type/manufacturer	Lightweight spherical replicated mirror/Talbert Reflector, Oakland, CA
Construction	Aluminum honeycomb/epoxy-fiberglass substrate
Mirror radius	14 ft
Mirror segment size	As per Figure 5 about 2-1/2 in. thick
No. of mirror segments	14
Mirror segment weight	120 lb (upper 7 segments) 80 lb (lower segments)
Mirror total weight	1400 lb
Mirror total area	About 450 sq ft
Optical coating	Vacuum deposited aluminum with SO_2 overcoat
Surface accuracy	5 arc min/ft slope error with no visible distortions
Total mirror cost	450K

and a contrast ratio of 20 to 1. To eliminate distortion in the final display, it is required that the normal path of rays from the projector be altered slightly to fit the array of object points determined in the optical analysis. This is referred to as predistorting the image.

The Hughes Company's liquid crystal projector is attractive from the standpoint that its scan lines can be shaped and thus furnish the necessary predistortion; however, current reports indicate that it is not developed sufficiently for color work. The output is reported by Hughes as 216 lumens. Only the monochrome version has been demonstrated and it appears to require considerable improvement in contrast and lag time.

The Eidophor projector is large (21 inches by 26 inches by 47 inches high), bulky (1100 lb) and costly (about $200,000) which makes this TV projector impractical. The Eidophor approach requires three color filtered units for each channel; however, its main advantage as a TV projector is that its light output is about 7000 lumens. The Eidophor Gretag 5171 projector utilizes 1029 TV lines and has a center of the picture resolution of about 800 TV lines.

The Electronic Systems Products, Inc. is in the process of developing a color TV projector with a resolution of 1029 TV lines, a brightness of 350 lumens, costing about 120K. The projector will be about 8 inches thick by 33 inches wide by 26 inches deep and will weigh about 125 lb.

A high brightness color light valve projector, with an output of 2700 lumens, is produced by Sodern in France. This projector has 625 TV lines, the physical size is large, and the cost is about $150,000. This TV projector, redesigned to utilize 1000 TV lines, might require a second look, because of the rear projection screen brightness problems, discussed in the next section of this report.

The smaller color television projectors such as Advent, Sony, Shannon, and Muntz are far too low in light output, being in the 75 lumens or lower category. Possible contending television projection techniques in the future are:

(a) Fluid deformation and Schlieren optics
(b) Membrane deformation and Schlieren optics
(c) Electro-optic crystal and polarized light (Philips)
(d) Liquid crystal and polarized light (Hughes)
(e) Photochromic effect
(f) Laser

Presently, the most attractive design is the General Electric Company's PJ5150 Light Valve Projector which will be on the commercial market in about mid 1979. The projector will present 1023 TV lines and produce a brightness of 500-700 lumens. The contrast is 25 to 1 with the measured fall-off in the corners of the field being 40 percent. Color is an established capability. The package size and weight are also attractive. It has dimensions of 22 inches high by 17 inches wide by 30.5 inches long, and weighs 130 lb. The cost of the General Electric Company's Light Valve Projector is about $85,000. The NAVAIRDEVCEN Off-Axis Visual Display system will utilize the General Electric Company's Light Valve Projector for both the Phase I and Phase II designs. The specifications for this projection system are summarized in Table 3.

A modified General Electric Company 2X lens adapter is utilized with the PJ5150 TV projector for both the Phase I and Phase II designs. The 2X lens adapter produces an 8 ft wide picture with a projector to screen dimensions of about 12 ft. The light valve projection system presents a picture with a 3 to 4 aspect ratio; however, the NAVAIRDEVCEN display design requires a square image of about 7.5 ft by 7.5 ft. The 2X lens adapter aperture must be modified to produce a square picture. An optical analysis of the projection system has determined that the

TABLE 3. TV PROJECTOR SPECIFICATION

Projector type/manufacturer	PJ5150 light valve projector/ General Electric Co.
Resolution	1023 TV lines, 800 horizontal, 650 vertical
Brightness	500 lumens (min)
Contrast	25 to 1
Input power	1200 watts
Wall power required	120V, 60 Hz, 20 amps
Size	22 in. high, 17 in. wide, 30.5 in. long
Weight	130 lb
Cost one unit	85K

cone of light distance from the TV projector to the rear projection screen is 188.5 inches.

As the rotating mirror in the Phase I design translates the real world image throughout the 180° field-of-view, the image also rotates. A de-rotational system must be introduced into the optical system so that the final viewer's image remains in the proper real world orientation. The most logical answer would be to utilize the de-rotational system already incorporated into the optical probe system; however, since the de-rotation would occur before the TV projection system, the final rear projection screen image might show a rotation of the TV lines. The total de-rotation problem could be remedied by modifying the 2X lens adapter to include a de-rotation prism system. The Phase II design has no image de-rotational problems.

2.3 Rear Projection Screen

The NAVAIRDEVCEN Off-Axis Wide Field-Of-View Display System will utilize a toroidal shaped rear projection screen configuration with a vertical plane radius of 78.2 inches and a horizontal plane radius of 101.3 inches. A 180° horizontal by 60° vertical field-of-view will require a toroidal shape size of 8 ft in height and a trapezoidal width of about 26 ft at the top and about 17.5 ft at the bottom. Obviously, a mosaicing of screen segments must be used to obtain the required size.

A study of the NAVAIRDEVCEN Off-Axis Display System's brightness requirements indicates that a screen gain greater than 1.29 is required. The display system with a 500 lumen output, from the General Electric PJ5150 TV projector, is not able to produce the required 5 ft lambert of brightness, utilizing a standard acrylic rear projection screen. The General Electric Company has suggested incorporating a Fresnel prism system, bonded on one side of the acrylic screen, to increase the

efficiency of the use of the light from the TV projector system. The Fresnel prism system design is fully described in Appendix A.

The rear projection screen, utilized by the NAVAIRDEVCEN Off-Axis Visual Display System, will consist of seven screen segments, each segment having a trapezoidal perimeter. The general dimensions for the seven segments are illustrated in Figure 13. The screen can conceivably be constructed by three vendors. The substrate has been postulated as stretched transparent acrylic. Once vendor (Swedlow, Inc. of Garden Grove, CA) forms the material with heat and pressure to a mold with the desired shape, a second vendor (Polacoat, Inc. of Cincinnati, Ohio) applies the diffusing layer. If a plain diffusing layer is used, it is preferably applied on the convex side of the molded substrate. If a Fresnel prism layer is applied, the diffusing coating is preferably applied on the concave side of the substrate. In either case, the diffusing coating is applied on the side of the substrate on which the abutted elements of the total screen are made flush while bonding them together. The Fresnel prism layer requires a third vendor to produce the individual Fresnel prism segments that will be bonded to the convex side of the substrate. The Swedlow, Inc. Company indicated that they might be able to provide a Fresnel prism about one-half the size of a screen segment. The total number of Fresnel prism segments required would then be 14.

Each rear projection screen segment weighs about 50 lb, while the total weight of the rear projection screen is 350 lb. The estimated cost of producing the total rear projection screen is about $75,000. The specifications for the rear projection screen are summarized in Table 4.

2.4 Rotating Mirror System

The Phase I design rotating mirror system, illustrated in Figure 3, consists of the General Electric Company's PJ5150 TV projector system and two folding optics mirrors. This assembly includes a stationary

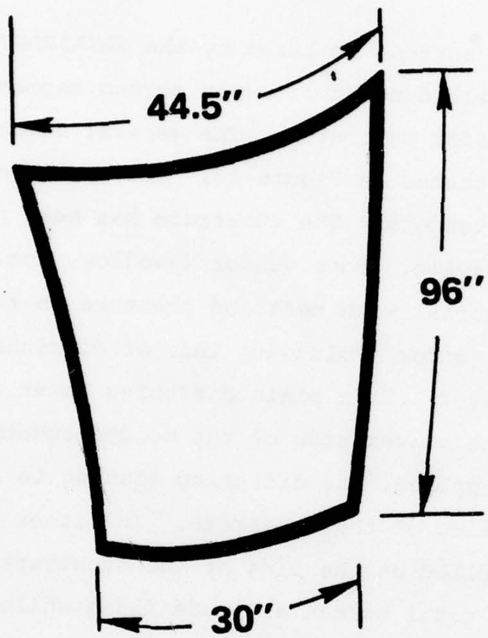

Figure 13. Rear Projection Screen Segment Dimensions

TABLE 4. REAR PROJECTION SCREEN SPECIFICATION

Screen type/manufacturer	Toroidal cast acrylic/ Swedlow Inc., Garden Grove, CA; Polacoat Inc., Cincinnati, OH
Construction	Stretched acrylic with diffusing coating and Fresnel-prism outer layer
Vertical radius	78.2 inches
Horizontal radius	101.3 inches
Number of acrylic segments	7
Number of Fresnel prism segments	14
Segment weight	50 lb
Total screen weight	350 lb
Screen size	About 174 sq ft
Screen segment size	As per Figure 7
Total screen cost	75K

3 ft by 2 ft mirror, and a 5 ft by 4 ft rotating mirror. A motor/potentiometer servo system is utilized to drive the 5 ft by 4 ft mirror, allowing the simulated real world image to be translated throughout the display's 180° field-of-view in 60° by 60° segments. The rotating mirror servo system is illustrated in Figure 14. This mirror servo system may be linked with the rhomb prism servo system in the NAVAIRDEVCEN Optical Probe, which is utilized on a terrain model scene generator system. The rhomb system is rotatable about the probes azimuth axis to allow for the viewing of the terrain model over a 360° field-of-view and also in 60° segments.

By utilizing the mirror manufacturing process of cast epoxy on a rigid honeycomb aluminum structure, the weight of the 5 ft by 4 ft mirror can be kept to a maximum of about 60 lb. This mirror can be purchased from the Talbert Reflector Company, Oakland, CA, on a special order.

The moment of inertia (I_3) of the rotating mirror system about axis no. 3 is calculated to be about 45 in. lbs sec^2 utilizing the formula

$$I_3 = 1/2\ mr^2$$

where

I_3 = inertia about axis no. 3 (in. lbs sec^2)

m = mass $\left(\frac{\#\text{sec}^2}{\text{in.}}\right)$

r = rad (in.)

The formula for transferring the moment of inertia equivalent to axis no. 2 is

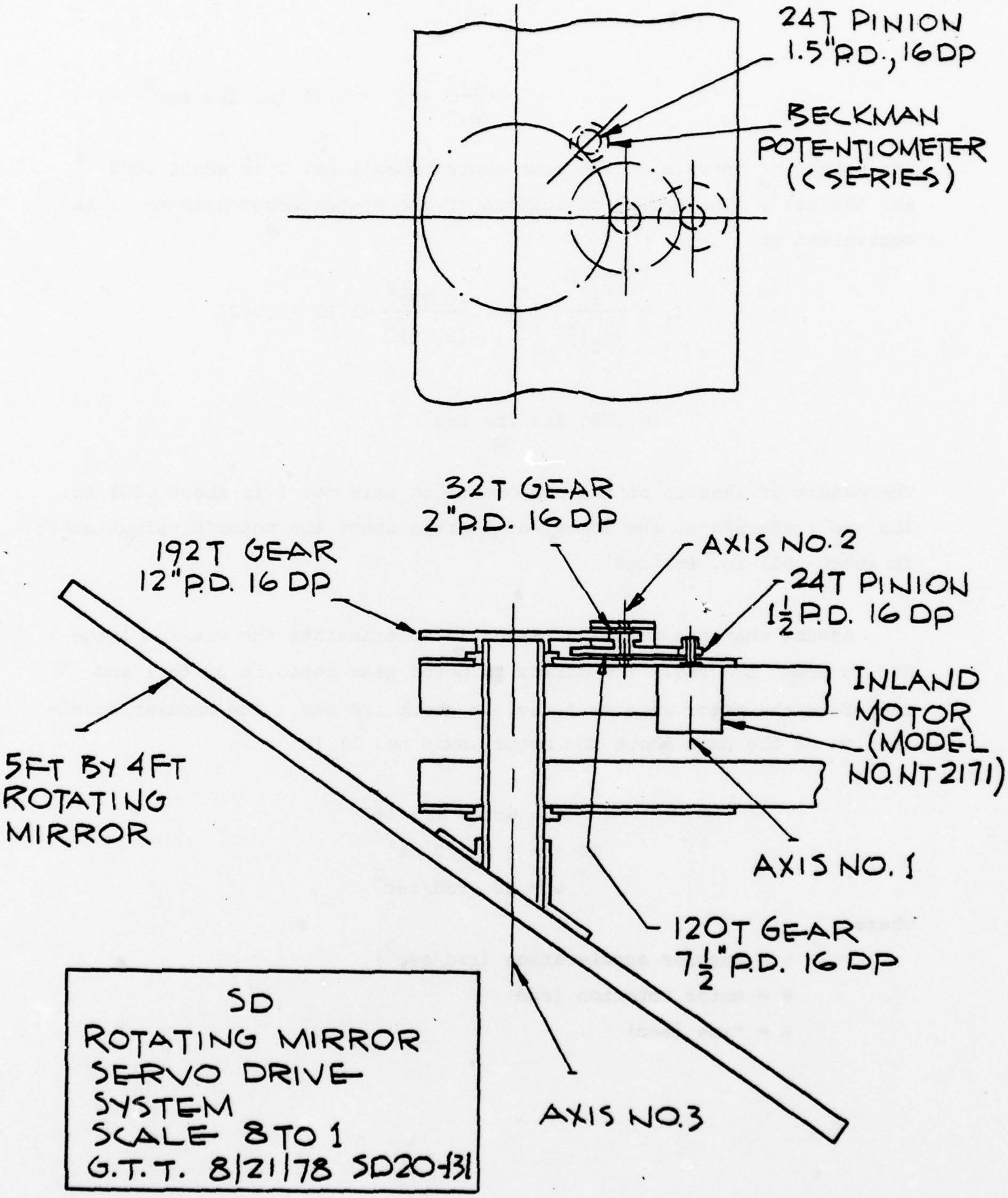

Figure 14. Rotating Mirror/Servo Drive System

$$I_2 = \frac{(r_2)^2}{(r_3)^2} (I_3)$$

$$= \frac{(1)^2}{(6)^2} (45) = 1.25 \text{ in. lbs sec}^2$$

The moment of inertia of the components on axis no. 2 is about .002 in. lbs sec^2. The moment of inertia of the system about axis no. 1 is equivalent to

$$I_1 = \frac{(r_1)^2}{(r_2)^2} (I_2) = \frac{(0.75)^2}{(3.75)^2} (1.25 + .002)$$

$$= .050 \text{ in. lbs sec}^2$$

The moment of inertia of the components on axis no. 1 is about .001 in. lbs sec^2; therefore, the moment of inertia about the motor's output shaft is about .051 in. lbs sec^2.

Assume that the rotating mirror is to translate the viewing image 60° in about 1/2 sec. The mirror to motor gear ratio is 30 to 1 and therefore the motor rotates 5 rev. in about 1/2 sec. The angular acceleration of the mass about the motor (axis no. 1) is

$$\theta = Wot + 1/2\ \alpha t^2$$
$$10\ \pi = 0 + 1/2\ \alpha t^2$$
$$\alpha = 30 \quad \text{rad/sec}^2$$

where

α = angular acceleration (rad/sec^2)

θ = motor rotation (rad)

t = time (sec)

The motor velocity after 1/2 sec is:

$$\begin{aligned} Wt &= Wo + \alpha t \\ &= 80\pi\ (1/2) \\ &= 125 \text{ rad/sec} \\ &= 1187 \text{ rpm} \end{aligned}$$

where

W_f = angular velocity after 1/2 sec

W_o = initial angular velocity

The servo motor torque (τ) required is:

$$\tau = I\alpha$$
$$\tau = .051\ (80\pi)$$
$$\tau = 12.8 \text{ in lbs}$$
$$\tau = 205 \text{ in oz}$$

The servo-motor selected is the Inland Motor Housed D.C. Servo-Motor (Model Number NT-2171). This motor provides a peak torque of 300 oz in at a no load speed of 1977 rpm. The motor specifications are summarized in Table 5.

The mirror/potentiometer gear ratio is 8 to 1. The mirror rotates a total of 120° (1/3 rev), while the potentiometer rotates 960° (2.66 rev). The servo system requires a 3 turn potentiometer. The potentiometer selected is the Beckman Instrument Company's 3 turn helipot (model No. C series). The potentiometer specifications are summarized in Table 6.

The amplifier was selected by the Kollmorgen Corp. (Inland Motor Division) as being compatible with their NT-2171 Servo Motor. The amplifier specifications are summarized in Table 7.

TABLE 5. ROTATING MIRROR MOTOR SPECIFICATIONS

Motor type	Housed D.C. Permanent Magnet Servo-Motor
Manufacturer	Inland Motor Division Killmorgen Corp. 501 First Street Radford, VA 24141
Model number	NT-2171
Peak torque	300 oz in
No load speed	1977 rpm
Horsepower	about 1/2
Size	4 in. dia by 4.5 in. long

TABLE 6. POTENTIOMETER SPECIFICATIONS

Potentiometer type	3 turn wirewound
Manufacturer	Beckman Instrument 2500 Harbor Blvd Fullerton, CA 92634
Model number	C series
Resistance range (ohms)	5 to 194,700
Size	1-3/16 in. dia. by 1-13/64 in. long

TABLE 7. AMPLIFIER SPECIFICATIONS

Amplifier type	D.C. Servo Amplifier
Manufacturer	Inland Motor Division 501 First Street Radford, VA 24141
Model number	EM-1809-00-B
Output power	50V @ 20 amps (1000 watts)
Input voltage	+50 to 60 volts
Frequency response	
(small signal)	10,000 Hz
(large signal)	400 Hz
Size	5 in. by 5 in. by 8 in.
Weight	5-1/2 lb

The diametral pitch of the servo gear system is determined using the formula:

$$\text{Allowable hp} = \left. \frac{S(Y)(F)(KV)(V)}{DP\ (33{,}000)} \right|^{a}$$

where

$$1/2 = \frac{(25{,}000)(.296)(.375)(.760)(189)}{DP\ (33{,}000)}$$

DP = 24

S = allowable working stress (PSI)

Y = tooth form factor

F = gear face width (in.)

K_V = dynamic load factor $\left[\frac{(600)}{(600+V)}\right]$

V = pitching velocity [(PD)(RPM)(.262)] (ft/min)

DP = diametral pitch

The diametral pitch selected for the rotating mirror servo system is 16.

The required optical predistortion for the NAVAIRDEVCEN (Phase I) Off-Axis Visual Display system will be incorporated into the 5 ft by 4 ft folding optical mirror. The General Electric Report (Appendix A) describes in detail the predistortion requirements, including predistortion plots (G.E. Figure 15) and a table (G.E. Table 3) showing the direction cosines of the normals at the given points on the mirror surface.

2.5 Stationary Mirror System

The three Phase II design stationary mirror systems, illustrated in Figure 4, consist of the General Electric Company PJ5150 TV projector system and two folding optics mirrors. This assembly includes an 8 inch by 10 inch lower mirror and a 16 inch by 16 inch upper mirror. These

[a] Philadelphia Gear Catalog, p. 20

front surface glass mirrors can be purchased from Edmund Scientific Company, Barrington, NJ. An 8 inch by 10 inch mirror (catalog number 41,321) is about 1/4 thick, and a 16 inch by 16 inch mirror (catalog number 85,206) is also about 1/4 thick.

The required optical predistortion for the NAVAIRDEVCEN (Phase II) Off-Axis Visual Display system will be incorporated into the 16 inch by 16 inch folding optical mirror. The General Electric Report (Appendix A) also describes these predistortion requirements, including a table (G.E. Table 4) showing the direction cosines of the normals at the given points on the mirror surface.

3.0 Task III - Visual Simulation Display Component Support Design

The NAVAIRDEVCEN Off-Axis Visual Display system component support designs will be presented in the following layout and assembly drawings:

- NAVAIRDEVCEN Off-Axis Display Structural Design Layout (SD20-10), Figure 15
- Display Main Structure Assembly (SD20-20), Figure 16
- Display Base Structure Assembly (SD20-50), Figure 17
- Display Cockpit Base Structure Assembly (SD20-70), Figure 18
- Display Mirror Structure Assembly (SD20-90), Figure 19
- Display Screen Structure Assembly (SD20-110), Figure 21
- Display Rotating Mirror System Assembly (SD20-130), Figure 22
- Display Stationary Mirror System Assembly (SD20-160), Figure 23

The structural design layout, Figure 15, includes both the Phase I design concept, which utilizes a single TV projector and rotating mirror system to obtain a 180° field-of-view, and the Phase II design concept, which utilizes 3 TV projectors to obtain the 180° field-of-view. The Phase I and Phase II designs will utilize the same spherical mirror and rear projection screen, and, therefore, drawings SD20-20, -50, -70, -90 and -110 will be the same for both designs. The Phase I design concept utilizes the display rotating mirror system assembly (SD20-130), while the Phase II design concept utilizes a stationary folding mirror system (SD20-160).

The structural layout drawing (SD20-10) shows a cockpit enclosure, which is not included in the scope of this report. Also shown is the structural base of a Singer Company's six degree-of-freedom motion system. This motion system, described and illustrated in Section 3.8 of this report, is included in the design of the display system, and

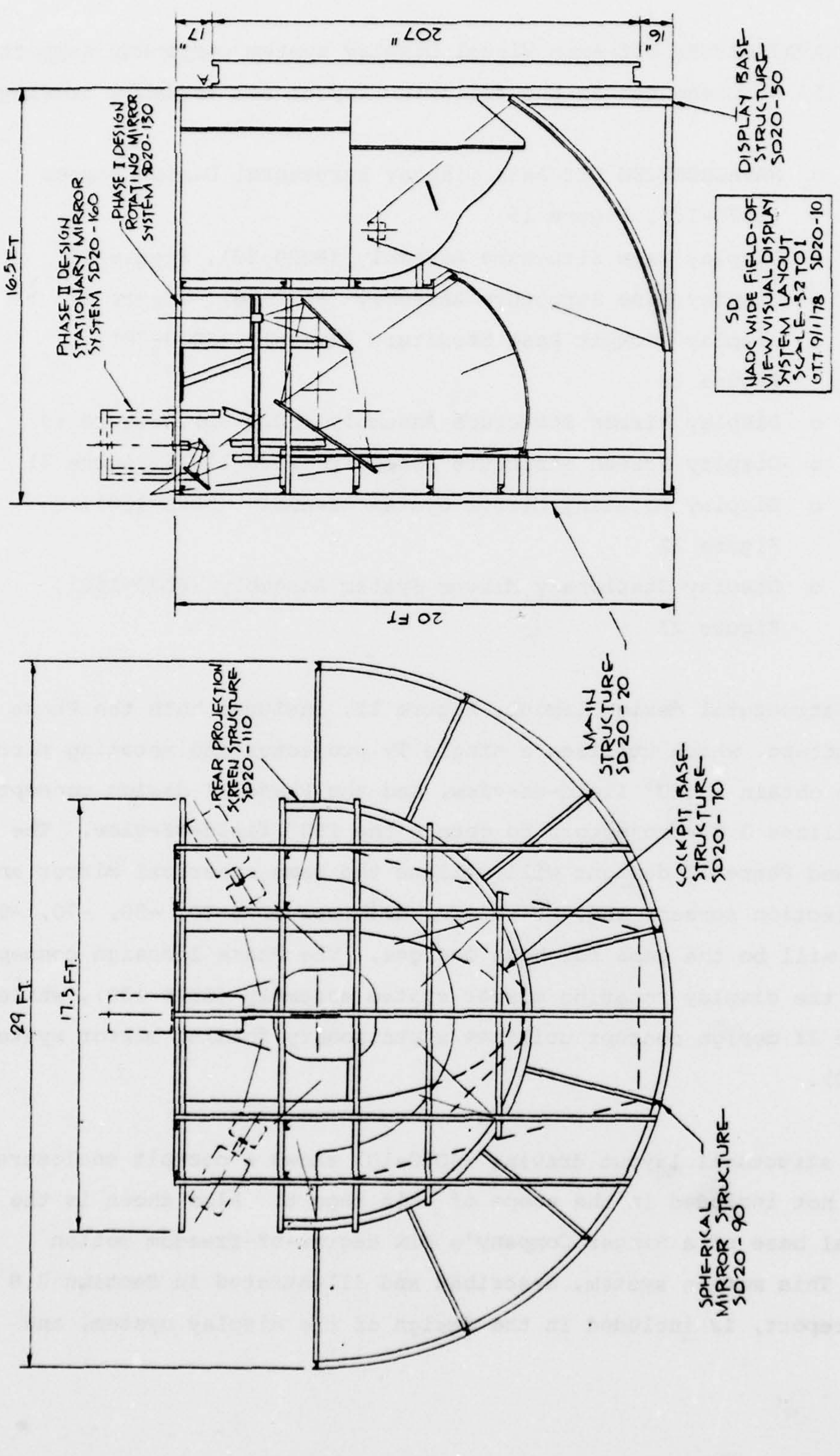

Figure 15. NAVAIRDEVCEN Off-Axis Display Structural Design Layout

the display base structure is shaped to conform to this motion system base.

3.1 Main Structure

The NAVAIRDEVCEN Visual Display main structure, illustrated in Figure 16, is designed to facilitate the Phase I design rotating mirror system as well as to allow for the Phase II design. The main structure consists of 3 inch aluminum channel and angle, bolted together in such a way as to provide the necessary rigidity for the display system. Structure is eliminated in areas that would interfere with the Phase I or Phase II optics, or the cockpit enclosure.

3.2 Base Structure

The base structure, illustrated in Figure 17, is designed to conform to the dimensions of the Singer Company's six degree-of-freedom motion system base. The base structure is designed typically with 4 inch aluminum channel, bolted together. Finger-like structural channel is extended from the base and will provide the base support for the display mirror structure. Additional mirror support could include channel structure secured to the motion base, and supporting the finger-like structural channels.

3.3 Cockpit Base Structure

The cockpit base structure, illustrated in Figure 18, raises the aircraft cockpit sufficiently off the motion base to allow for a 40° downview throughout the 180° horizontal fild-of-view. The overall dimensions of the cockpit base are such that a side-by-side cockpit configuration, as well as a rear aircraft compartment, may be accommodated. The cockpit base structure is designed to align with the main base structure, and also to allow for the incorporation of a McFadden Electronics Company aircraft stick and rudder system (Catalog Number 392A).

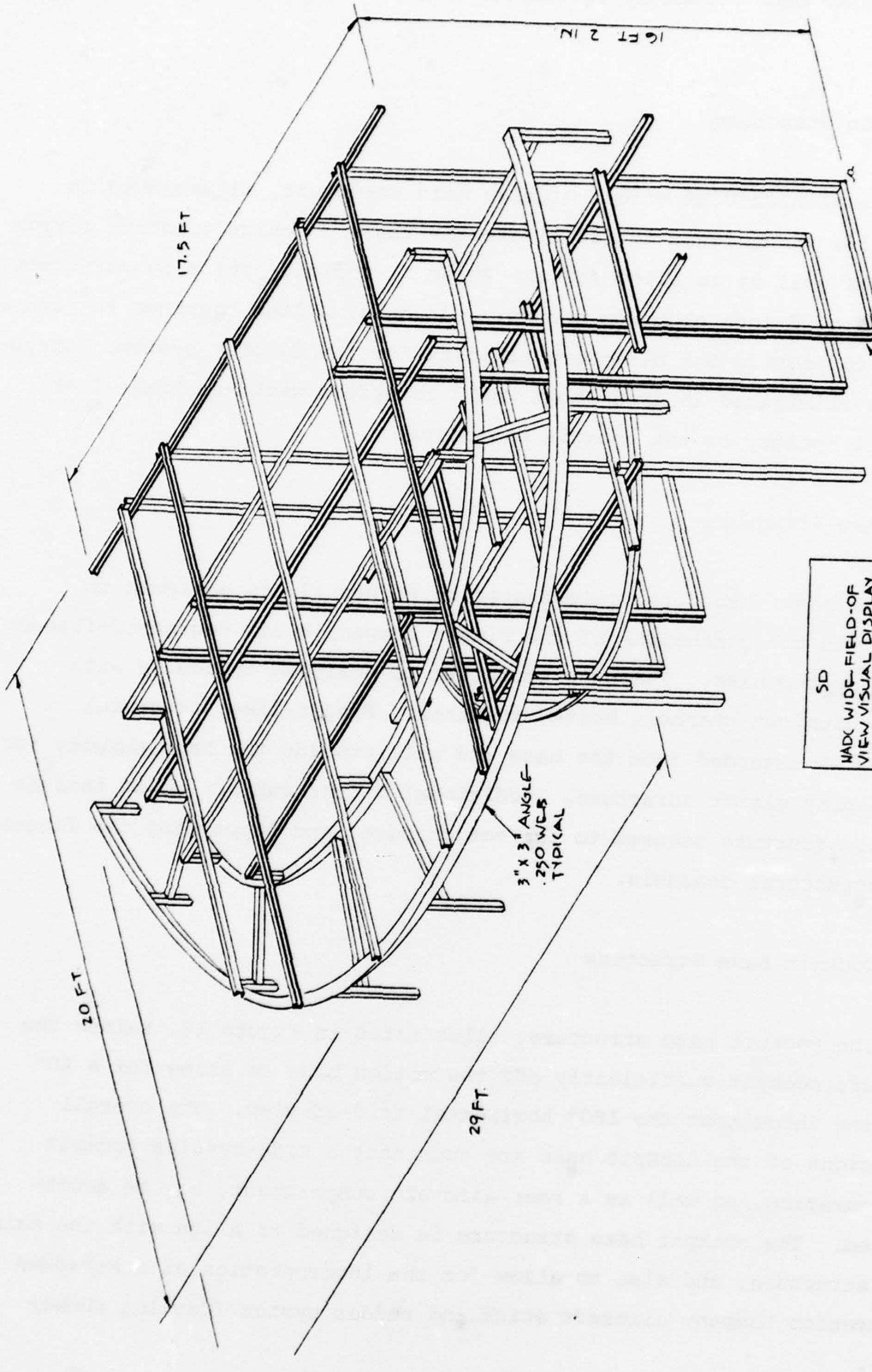

Figure 16. Display Main Structure Assembly

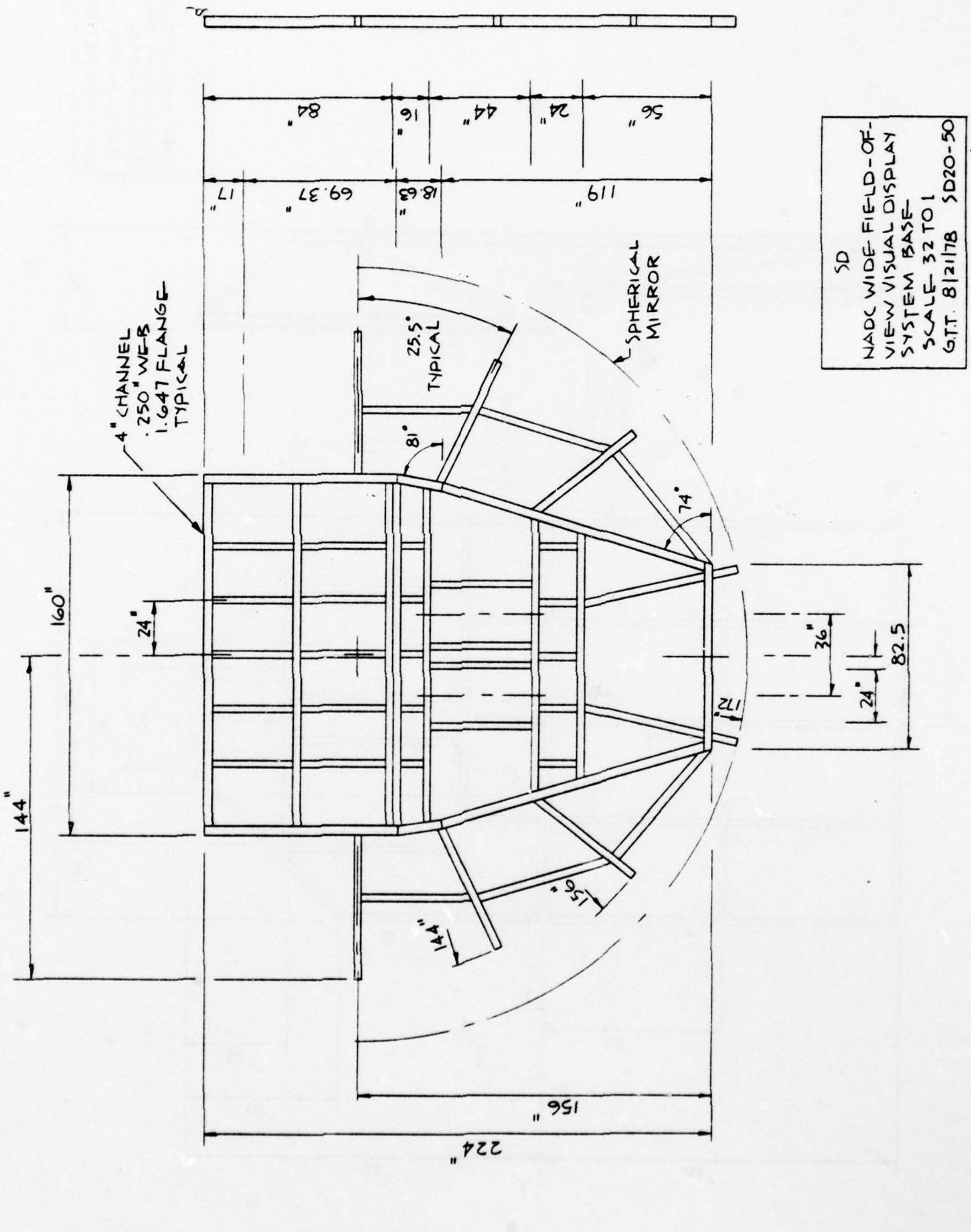

Figure 17. Display Base Structure Assembly

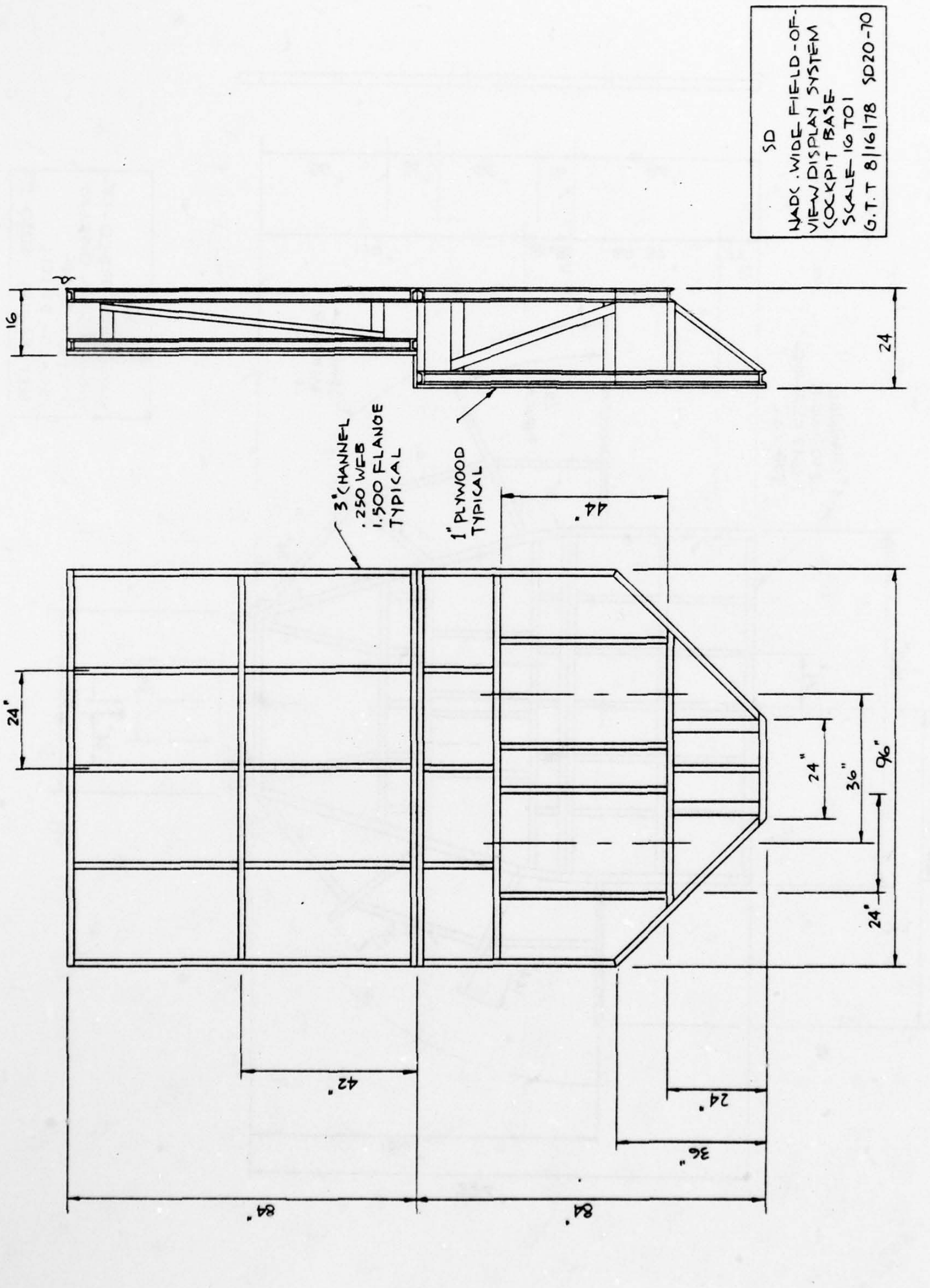

Figure 18. Display Cockpit Base Structure Assembly

3.4 Mirror Structure

The mirror structure, illustrated in Figure 19, consists of a 4 inch channel, a 3 inch angle, and a 2 inch by 3 inch channel to provide a structure rigid enough to support the weight of the spherical mirror. Many of the structural supports for the mirror structure require large bending radii to conform to the spherical radius of the mirror. The NAVAIRDEVCEN fabrication shop is capable of this structural bending operation.

Several L-shaped angles could be attached to the back edge of each mirror segment so that each segment may be aligned properly with each adjacent segment. The general mirror segment/display structure fastening technique is illustrated in Figure 20. Obviously, a certain amount of fitting and shimming is required to align one mirror segment with another.

3.5 Rear Projection Screen

The rear projection screen structure, illustrated in Figure 21, supports the seven screen segments at top and bottom from two 3 inch by 3 inch angles surrounding the periphery of the screen, as illustrated on the main structure assembly. The projection screen segments must be fastened together at assembly.

3.6 Rotating Mirror Structure

The Phase I design rotating mirror support system, illustrated in Figure 22, is a design structure which contains the General Electric light valve projector system and the folding optics mirrors. The rotating mirror structure consists primarily of 3 inch channel, and 1/4 inch plate material, in a self-contained structural subassembly. The rotating mirror itself is supported from a piece of 4 inch dia-tubing, which in turn is supported by two 5 inch flanged ball bearings. The rotating mirror servo system is mounted on the upper 1/4 inch plate.

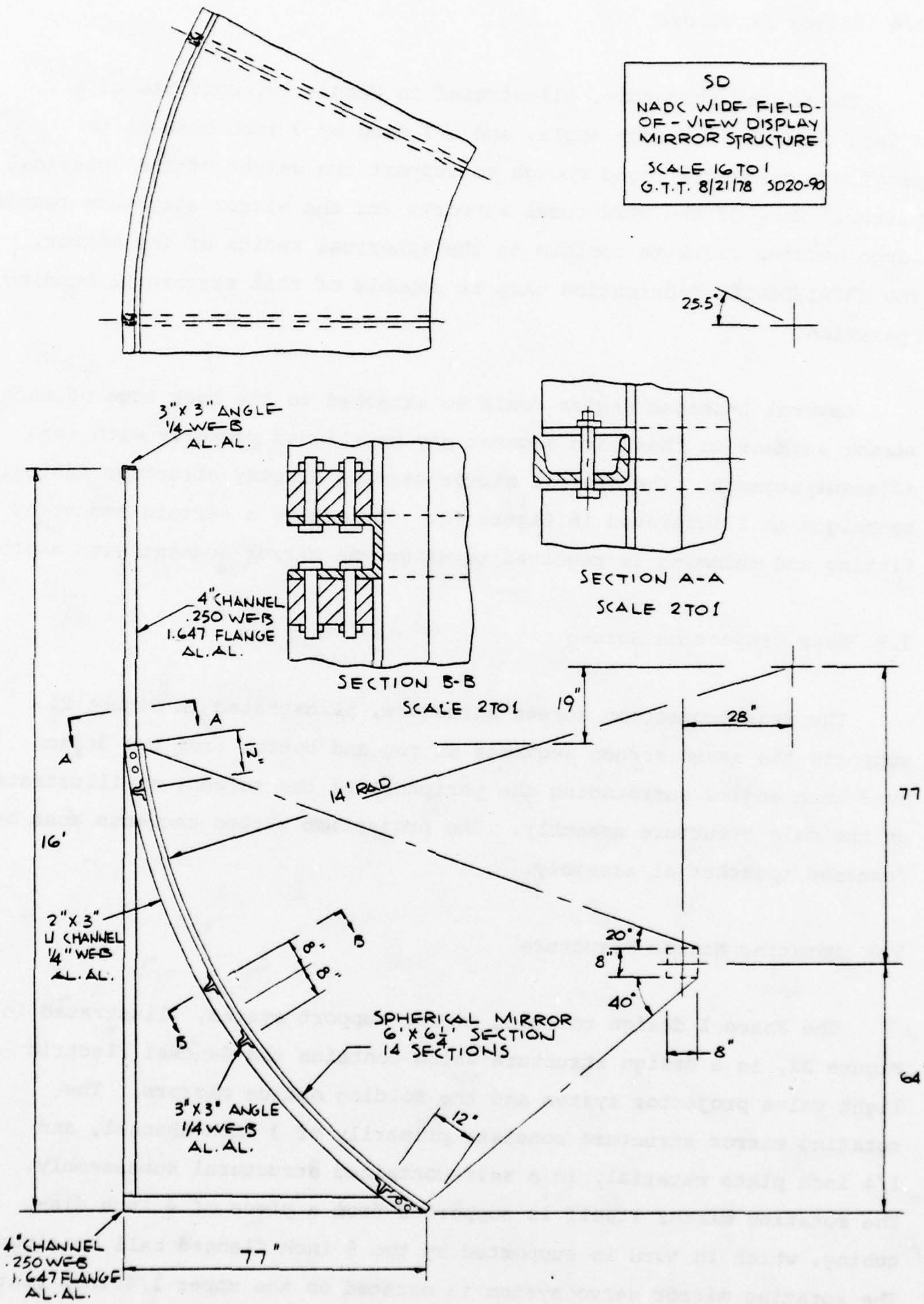

Figure 19. Display Mirror Structure Assembly

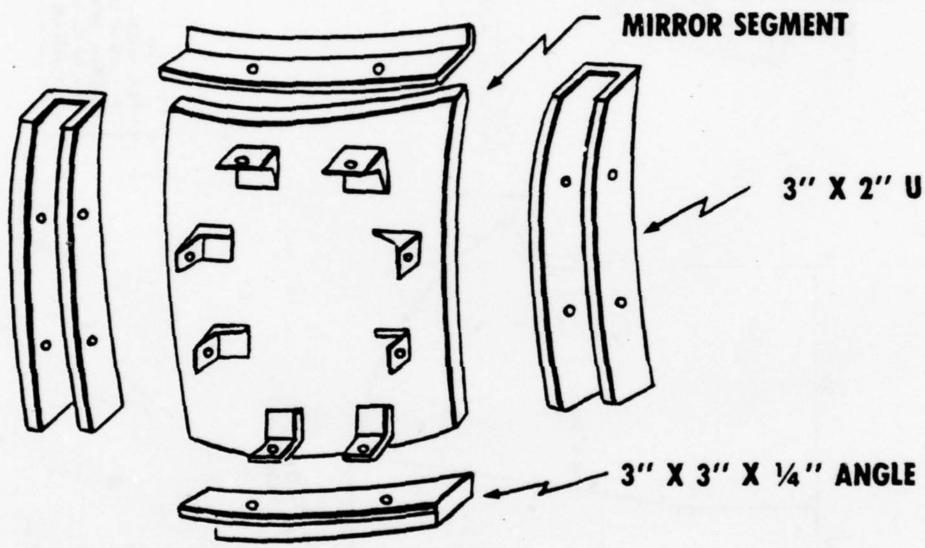

Figure 20. Mirror Segment Fastening Technique

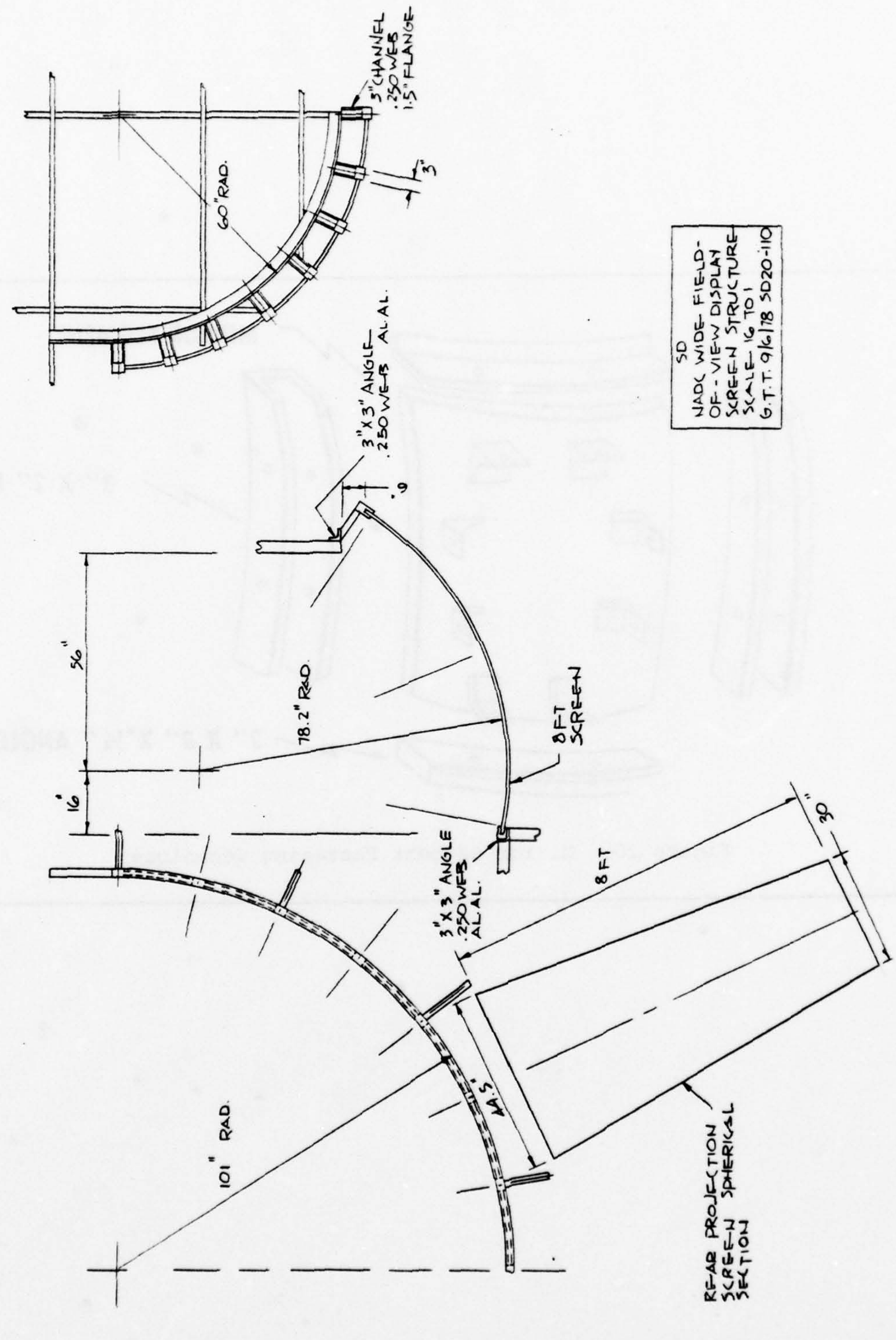

Figure 21. Display Screen Structure Assembly

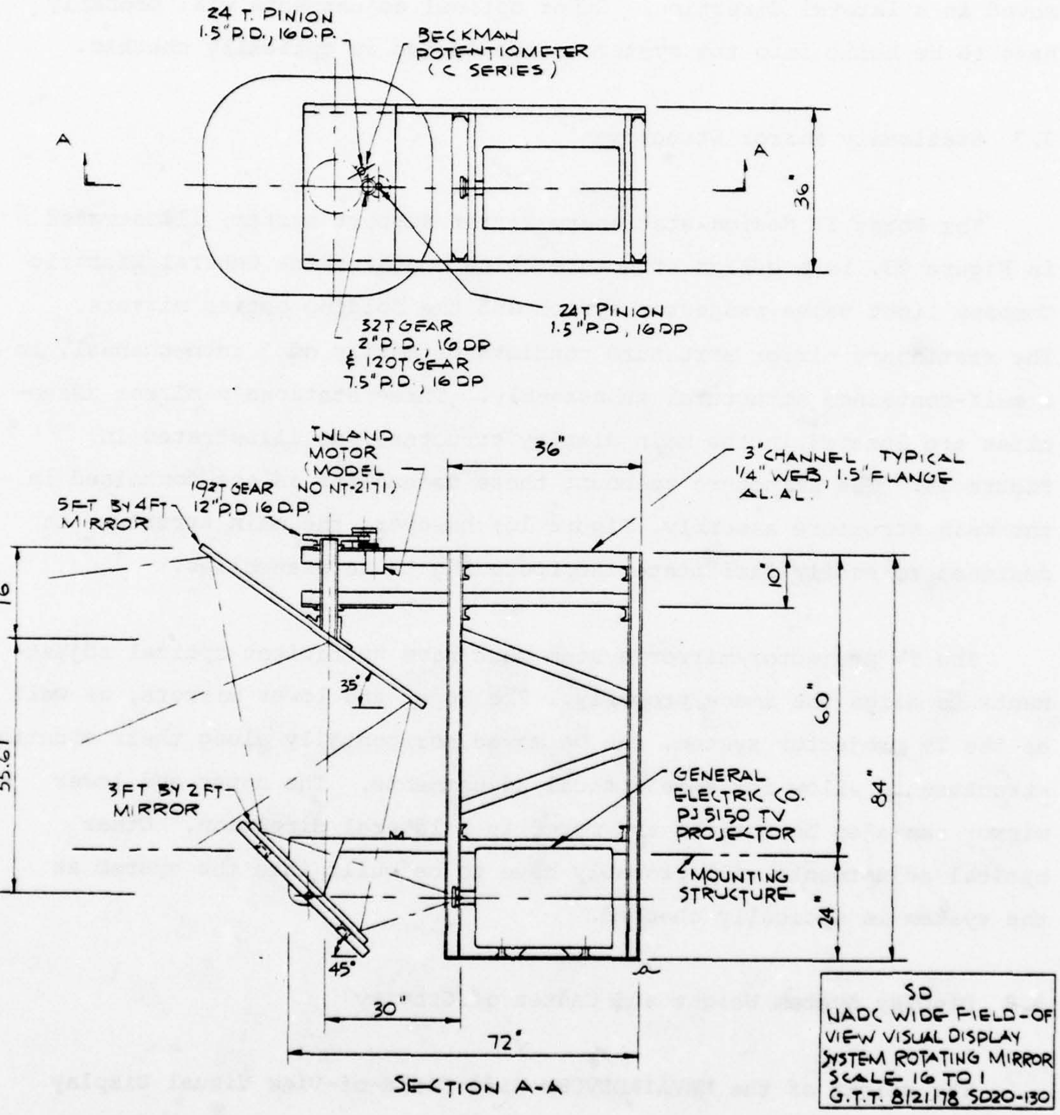

Figure 22. Display Rotating Mirror System Assembly

The TV projector/mirror system must have sufficient optical adjustments to align the image properly. The lower mirror and TV projector can be moved horizontally along their mounting structure to allow for some optical adjustments. The lower mirror can also be rotated and moved in a lateral direction. Other optical adjustments will probably have to be built into the system as the system is optically checked.

3.7 Stationary Mirror Structure

The Phase II design stationary mirror support system, illustrated in Figure 23, is a design structure which contains the General Electric Company light valve projector system and the folding optics mirrors. The stationary mirror structure consists primarily of 3 inch channel, in a self-contained structural subassembly. Three stationary mirror assemblies are located in the main display structure, as illustrated in Figure 15. The structure to mount these assemblies is not contained in the main structure assembly, Figure 16; however, the main structure is designed to easily facilitate incorporating these assemblies.

The TV projector/mirror system must have sufficient optical adjustments to align the image properly. The upper and lower mirrors, as well as the TV projector system, can be moved horizontally along their mounting structure to allow for some optical adjustments. The upper and lower mirror can also be rotated and moved in a lateral direction. Other optical adjustments will probably have to be built into the system as the system is optically checked.

3.8 Display System Weight and Center of Gravity

The weight of the NAVAIRDEVCEN Wide Field-of-View Visual Display system is particularly important if the system is to be located in the Singer Company six degree-of-freedom motion system. This system is illustrated in Figure 24. This motion system will allow an 18,000 lb payload. The center of gravity is also important if the display system

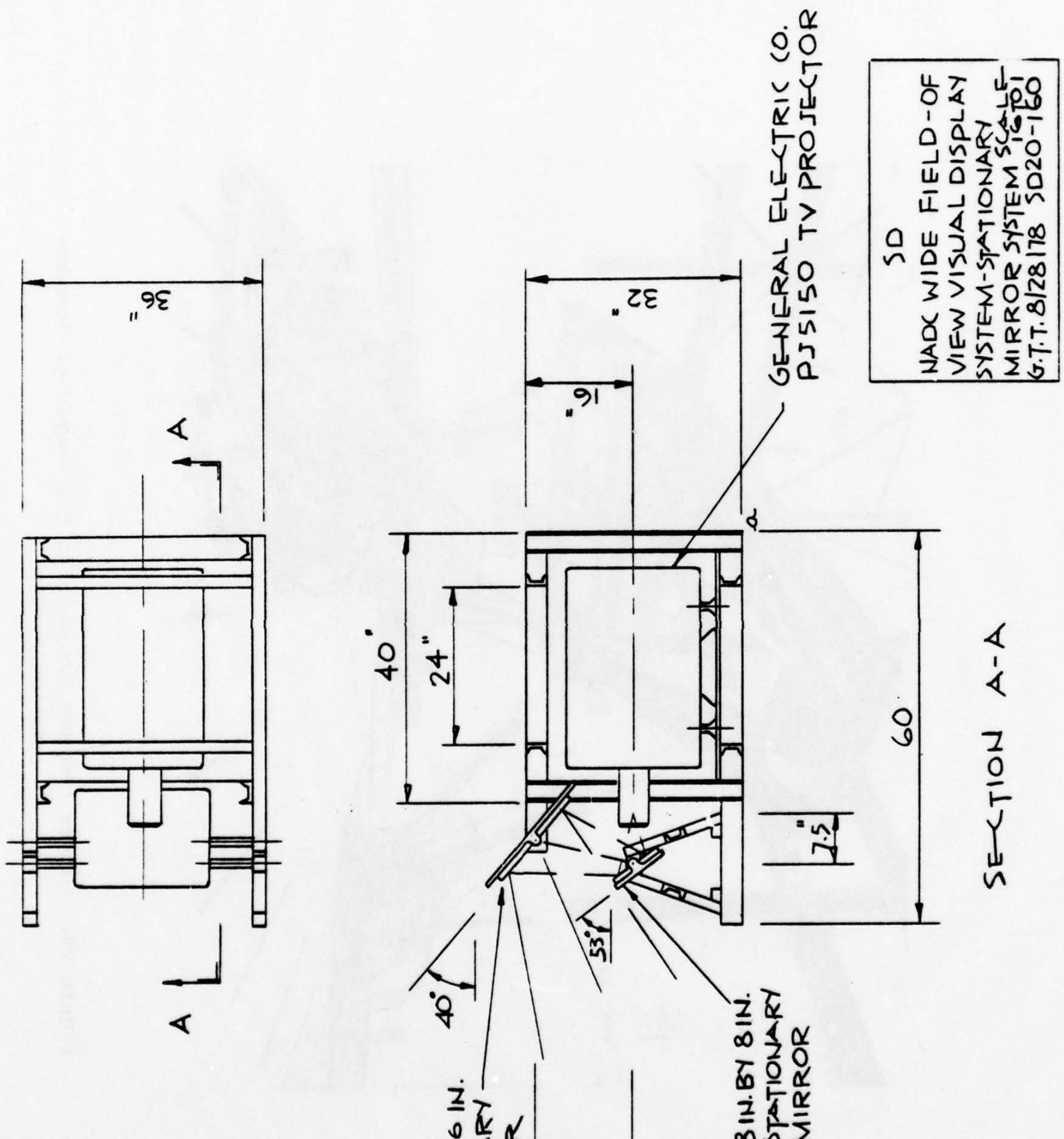

Figure 23. Display Stationary Mirror System Assembly

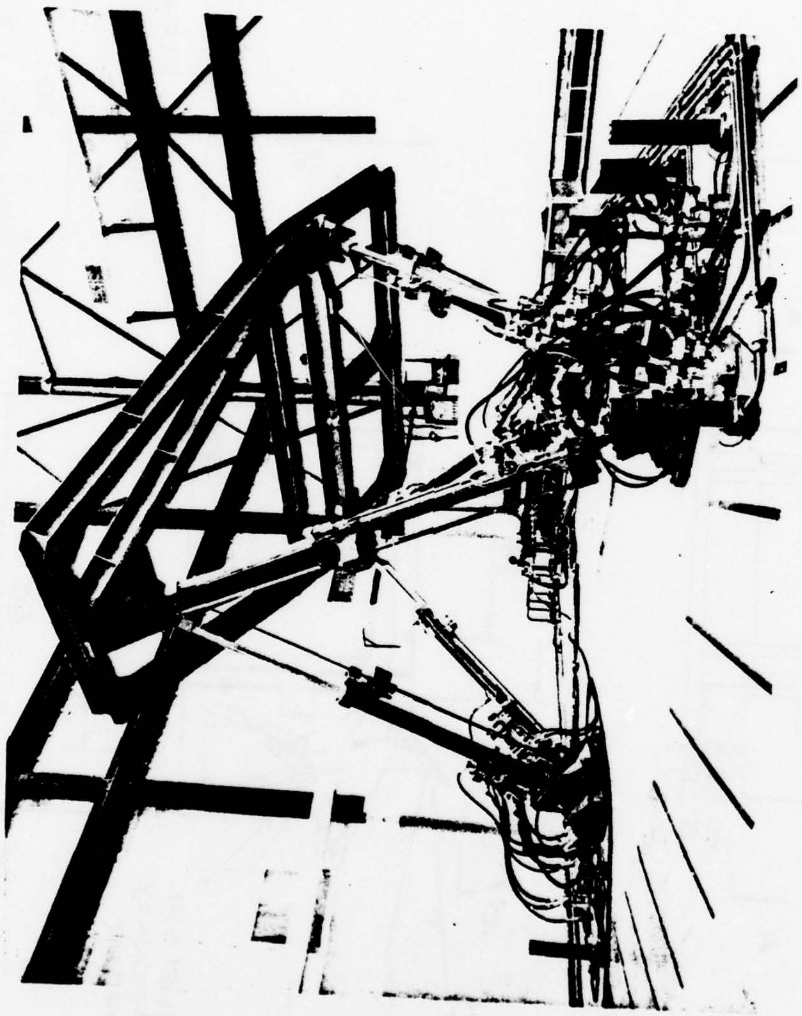

Figure 24. Singer Company Synergistic Six Degree-of-Freedom Motion System

is located on a motion system. Ideally, the horizontal center of gravity dimensions of the total system should be located at the centroid pattern for upper and lower actuator arm joints. This point is located 100 inches from the back of the motion base structure. Also, the vertical center of gravity dimension should be located as low as possible, but not more than 50 inches off the motion base. The visual display main structure, with an overall horizontal dimension of 20 ft, was arbitrarily centrally located on the Singer Company motion base, as illustrated in Figure 15.

The weight and center of gravity of each individual structural assembly have been calculated and these values are documented in Table 8. The horizontal and vertical center of gravity dimensions of individual structural assemblies are located from a point, marked "a", shown on drawings (SD20-20, -50, -70, -130, -160). The lateral center of gravity point is assumed to be on the center line of the structure, since all structural assemblies are symmetrical. The weight and center of gravity of the simulator's cockpit and cockpit personnel are estimated so that a complete weight analysis can be documented. These center of gravity dimensions are located from a point, marked "A", shown on the structural layout drawing (SD20-10). The center of gravity points for the spherical mirror and rear projection screen assemblies are also located from point A on the structural layout drawing.

The Phase I system design weighs a total of 11,256 lb, which includes a wide field-of-view display system weight of 5546 lb. The Phase II system design weighs a total of 11,598 lb, which includes a wide field-of-view display system weight of 5800 lb.

The Phase I and II design center of gravity locations for each system item are illustrated in Figure 25, with each assembly being located from point A. The overall Phase I and Phase II design center of gravity locations for the total system are also shown. The data shown on Figure 25 corresponds to the data shown in Table 8. The Phase I system design center of gravity is 12 inches back of the centroid of

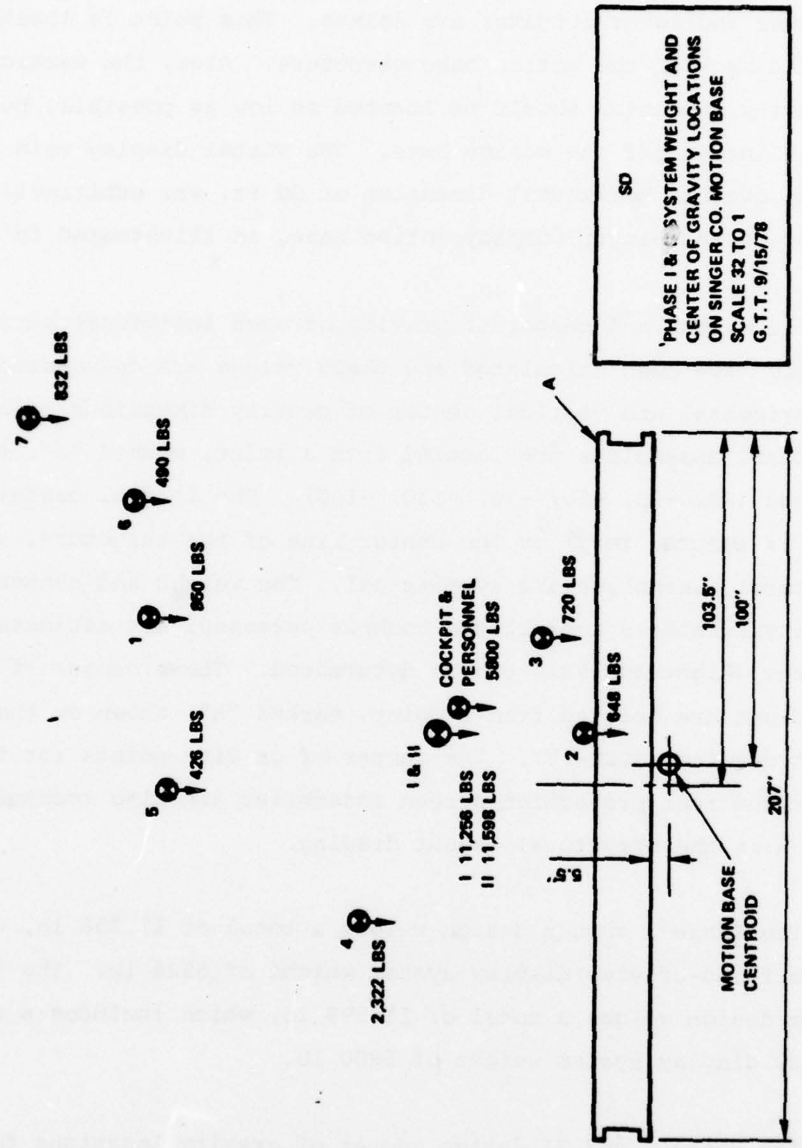

Figure 25. System Weight and Center of Gravity Locations on Singer Company Motion Base

TABLE 8. SYSTEM WEIGHT AND CENTER OF GRAVITY LOCATIONS

System Item	Weight (lb)	Center of Gravity From Point a (in.)		Center of Gravity From Point A (in.)	
		Horiz	Vert	Horiz	Vert
o Aircraft cockpit system (including displays, instruments, cables, etc.)	5,000 (max allowed)	-	-	79	42
o Personnel	800	-	-	79	42
o Display system					
(1) Main structure	850	71	133	54	137.5
(2) Base structure	648	104	2	87	2
(3) Cockpit base structure	720	76	12.5	59	16.5
(4) Mirror structure	2,322	-	-	144	70.5
(5) Screen structure	426	-	-	107	129
(6) Rotating mirror structure	490	35.5	41	18.5	140.5
(7) Stationary mirror struc.	832	25.5	14.5	-5.5	170
Phase I Design Total	11,256	-	-	88	48.5
Phase II Design Total	11,598	-	-	84.5	53.5

pattern for the upper and lower motion actuator arm joints, and 48.5 inches above the motion base. The Phase II system design center of gravity is 15.5 inches back of the centroid, and 53.5 inches above the motion base.

Adding a 1000 lb of weight at the nose of the motion base would locate the simulator system's horizontal center of gravity at the motion base centroid, and also lower the vertical center of gravity by about 4 inches. This additional weight could be utilized as extra support structure for the spherical mirror assembly. The total flight simulator weight would be well under the 18,000 lb motion system total payload.

4.0 Task IV - NAVAIRDEVCEN Wide Field-Of-View Display System Fabrication Cost and Schedule Estimates

The cost and schedule estimates were determined according to the component support design layout and assembly drawings. The detailed costing information is not included in this report; however, the following summary is provided.

4.1 Cost Summary Estimates

Phase I Design		
Labor cost		200K
Material/contracts		900K
	Total	1100K
Phase II Design		
Labor cost		200K
Material/contracts		1050K
	Total	1250K

The cost of converting the Phase I design to the Phase II design would be about 200K, assuming that the TV projector purchased for the Phase I design would be utilized as part of the Phase II design.

4.2 Schedule Estimate

For purposes of reducing the number of scheduling variables, a number of assumptions will be presented. The proposed schedule will require, ideally, a 1-1/2 year period to complete the fabrication of the Phase I or Phase II designs. The long lead item is the fabrication of the spherical mirror. To convert the Phase I design into the Phase II design would require about a 6 month period, providing the Phase I TV projector system contract is written in such a way that two more projectors could be purchased, utilizing the same Phase I single TV projector

contract. The Phase I or Phase II design schedule estimates will require one engineer for the period of the project, two design detailers, full time, for a period of about 3 or 4 months, one electrical/mechanical engineering technician, periodically, for a total effort of about 3 or 4 months, and three shop model makers, full time, for a period of about 9 months. The conversion of the Phase I design into a Phase II design requires one engineer, for the period of the conversion, one design detailer, for a period of about 1 month, one electrical/mechanical engineering technician, periodically, for a total effort of about 2 months, and two shop model makers, full time, for a period of about 2 or 3 months.

Table 9 details the scheduling estimates for completing the Phase I or Phase II tasks required to construct the NAVAIRDEVCEN Wide Field-of-View Visual Display System.

Table 10 details the scheduling estimates for converting the Phase I display system into the Phase II display system.

TABLE 9. NAVAIRDEVCEN WIDE FIELD-OF-VIEW VISUAL DISPLAY SYSTEM SCHEDULE ESTIMATE

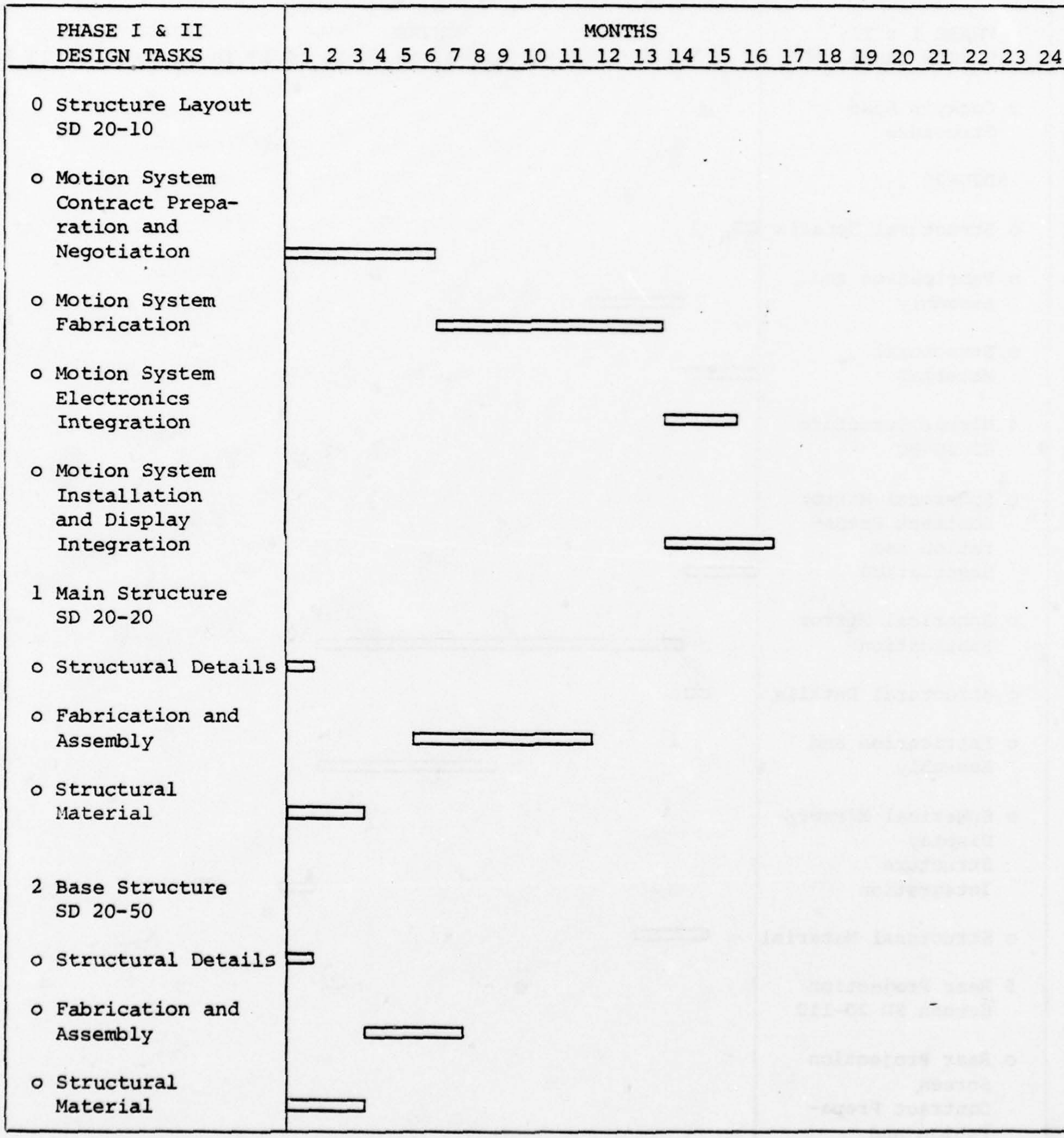

TABLE 9. NAVAIRDEVCEN WIDE FIELD-OF-VIEW VISUAL DISPLAY SYSTEM SCHEDULE ESTIMATE (cont)

PHASE I & II DESIGN TASKS	MONTHS 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
3 Cockpit Base Structure																								
SD20-70																								
o Structural Details	—																							
o Fabrication and Assembly				—	—	—	—																	
o Structural Material	—	—	—																					
4 Mirror Structure SD 20-90																								
o Spherical Mirror Contract Preparation and Negotiation	—	—	—																					
o Spherical Mirror Fabrication				—	—	—	—	—	—	—	—	—	—	—	—									
o Structural Details			—																					
o Fabrication and Assembly											—	—	—	—	—									
o Spherical Mirror/ Display Structure Integration																—								
o Structural Material			—	—	—																			
5 Rear Projection Screen SD 20-110																								
o Rear Projection Screen. Contract Preparation and Negotiation	—	—	—	—	—	—																		

TABLE 9. NAVAIRDEVCEN WIDE FIELD-OF-VIEW VISUAL DISPLAY SYSTEM
SCHEDULE ESTIMATE (cont)

PHASE I & II DESIGN TASKS	MONTHS 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
o Rear Projection Screen Fabrication																								
o Structural Details																								
o Fabrication and Assembly																								
o Rear Projection Screen/Display Structure Integration																								
o Structural Material																								

TABLE 9. NAVAIRDEVCEN WIDE FIELD-OF-VIEW VISUAL DISPLAY SYSTEM SCHEDULE ESTIMATE (cont)

PHASE I DESIGN TASKS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
6 Rotating Mirror System SD20-130																								
o TV Projector Contract Preparation and Negotiation	X	X	X	X	X	X																		
o TV Projector (Quan. 1) Fabrication							X	X	X															
o Adapter Lens (Quan. 1) Fabrication							X	X	X															
o 5 ft x 4 ft Mirror Purchase		X	X	X	X	X	X	X	X															
o 3 ft x 2 ft Mirror Purchase		X	X	X																				
o Rotating Mirror System Details		X																						
o Fabrication and Assembly							X	X	X	X														
o Structural Materials		X	X	X																				
o Servo Materials		X	X	X	X	X	X																	
o Servo Integration															X									
Phase I Visual Display System Integration, Optical and Checkout																	X	X						

TABLE 9. NAVAIRDEVCEN WIDE FIELD-OF-VIEW VISUAL DISPLAY SYSTEM SCHEDULE ESTIMATE (cont)

PHASE II DESIGN TASKS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
7 Stationary Mirror System SD20-160																								
o TV Projector Contract Preparation and Negotiation	▬	▬	▬	▬	▬	▬																		
o TV Projector (Quan. 3) Fabrication							▬	▬	▬															
o Adapter Lens (Quan. 3) Fabrication							▬	▬	▬															
o 8 in. x 10 in. Mirror		▬	▬	▬																				
o 16 in. x 16 in. Mirror		▬	▬	▬																				
o Stationary Mirror System Details		▬																						
o Fabrication and Assembly							▬	▬	▬	▬														
o Structural Materials		▬	▬	▬																				
o Projector/Display Integration															▬									
Phase II Visual Display System Ingegration Optical Registration and Checkout																	▬	▬						

TABLE 10. PHASE I TO PHASE II DISPLAY SYSTEM
CONVERSION SCHEDULE

PHASE II CONVERSION TASKS	MONTHS 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
7 Stationary Mirror System SD20-160	
o TV Projector Contract Negotiation	
o TV Projector (Quan. 2) Fabrication	
o Adapter Lens (Quan. 3) Fabrication	
o 8 in. x 10 in. Mirror	
o 16 in. x 16 in. Mirror	
o Stationary Mirror System Details	
o Fabrication and Assembly	
o Structural Materials	
o Projector/ Display Integration	
Phase II Visual Display System Integration Optical Registration and Checkout	

CONCLUSIONS

A wide field-of-view visual display system design, utilizing the off-axis reflective display concept is feasible. This display system is capable of being constructed on a Singer Company six degree-of-freedom motion system. The NAVAIRDEVCEN Wide Field-Of-View Visual Display system has the capability of presenting a real world color virtual image with a large (40°) down vision. This display system has a viewing volume width of 48 inches, allowing for side-by-side cockpit configurations. The Phase I display design, which utilizes a single TV projector/rotating mirror system to translate a 60° by 60° image over a 180° horizontal field-of-view, can be used directly with the NAVAIRDEVCEN Terrain Model, Scene Generator System. The NAVAIRDEVCEN Scene Generator System utilizes an optical probe, capable of producing a 60° by 60° field-of-view throughout the entire 360° azimuth axis. The Phase II display design which utilizes three TV projector/stationary mirror systems to produce a continuous 180° horizontal field-of-view cannot be used directly with the NAVAIRDEVCEN Terrain Model, Scene Generator System. The Phase II display design must utilize a computer generated image scene generator system or with a terrain model optical probe, which is capable of producing a 180° horizontal by 60° vertical field-of-view image. It should be noted that the Phase I and Phase II display designs are identical except for the TV projector/folding optics mirror assembly.

RECOMMENDATIONS

The NAVAIRDEVCEN Wide Field-Of-View Visual Display system plans and schedule estimates should be utilized to request funding to fabricate an experimental display prototype, so that the feasibility of the display design can be validated.

The electronic and optical interface requirements of the visual display system, with the required scene generator systems and computer equipment, should be explored. The Phase I and Phase II projector lens adapters must be designed.

Further investigation of TV projection system brightness should be pursued to eliminate the Fresnel lens requirement in the rear projection screen (described in Appendix A, pages 25 to 32).

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APPENDIX A

ANALYSIS REPORT OF THE NAVAIRDEVCEN OFF-AXIS VISUAL DISPLAY,
GENERAL ELECTRIC COMPANY,
SEP 1978

ANALYSIS REPORT

OF THE

NADC OFF-AXIS VISUAL DISPLAY

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

There has long been a need in aircraft simulation for a wide angle visual display that will accommodate the entire crew of a large aircraft.

This study is concerned with the approach and design of a wide angle display for multiple crewmembers in large aircraft simulators. The Study traces the development for this application from the conclusions of a previous study.

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ANALYSIS REPORT

OF THE

NADC OFF-AXIS VISUAL DISPLAY

SECTION 1

INTRODUCTION, SUMMARY, CONCLUSIONS

1.1 INTRODUCTION

In simulators for some types of aircraft it is desirable to employ an out-the-window display system capable of beign used simultaneously by two or more viewers, e.g., pilot, copilot, etc.

For a large viewing volume and a large field-of-view of 60 degrees vertical by 180 degrees horizontal it was found by L. Shaffer and J. Waidelich in their study for the Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio (a predecessor to this study) that the best system conceivable is an off-axis infinity display system consisting of a large spherical mirror (theirs was sixteen feet in radius), a toroidal rear projection screen, and three General Electric light-valve projectors, with a pair of predistortion mirrors between each projector and the rear-projection screen. See the report, Wide Angle Multi-Viewer Infinity Display, Air Force Contract No. F33615-76-C-64, September, 1977 for detials of how they arrived at this conclusion. Figure 1 of that study is reproduced here as Figure 1 depicting the arrangement of the viewing volume, spherical mirror, rear projection screen, projectors, and projection mirrors.

The goal of this study is to determine the optimal placement of the spherical mirror and screen for a viewing volume of 8 inches by 8 inches by 48 inches, to determine the placement and shape of the projection mirrors, and to discuss the materials used, general construction techniques, and cost of materials for components of this system. The projector and projector mirrors are placed for two display configurations:(1) Phase I, consisting of one projector and pair of predistortion mirrors, capable of rotating a 60 degree by 60 degree image throughout the 60 degree by 180 degree field of view and (2) Phase II, consisting of three projectors, each with a fold and predistortion mirror, the whole system fixed.

This report will discuss, first, the optical layout of the entire system, and then some remarks will be made concerning the materials and construction techniques.

During the early part of the study, the analysis was for a field of view between ± 30 degree elevation and for a 12 inch by 12 inch by 48 inch viewing volume. Later in the study the system was defined to be a +20 degree to -40 degree field of view for an 8 inch by 8 inch by 48 inch viewing volume.

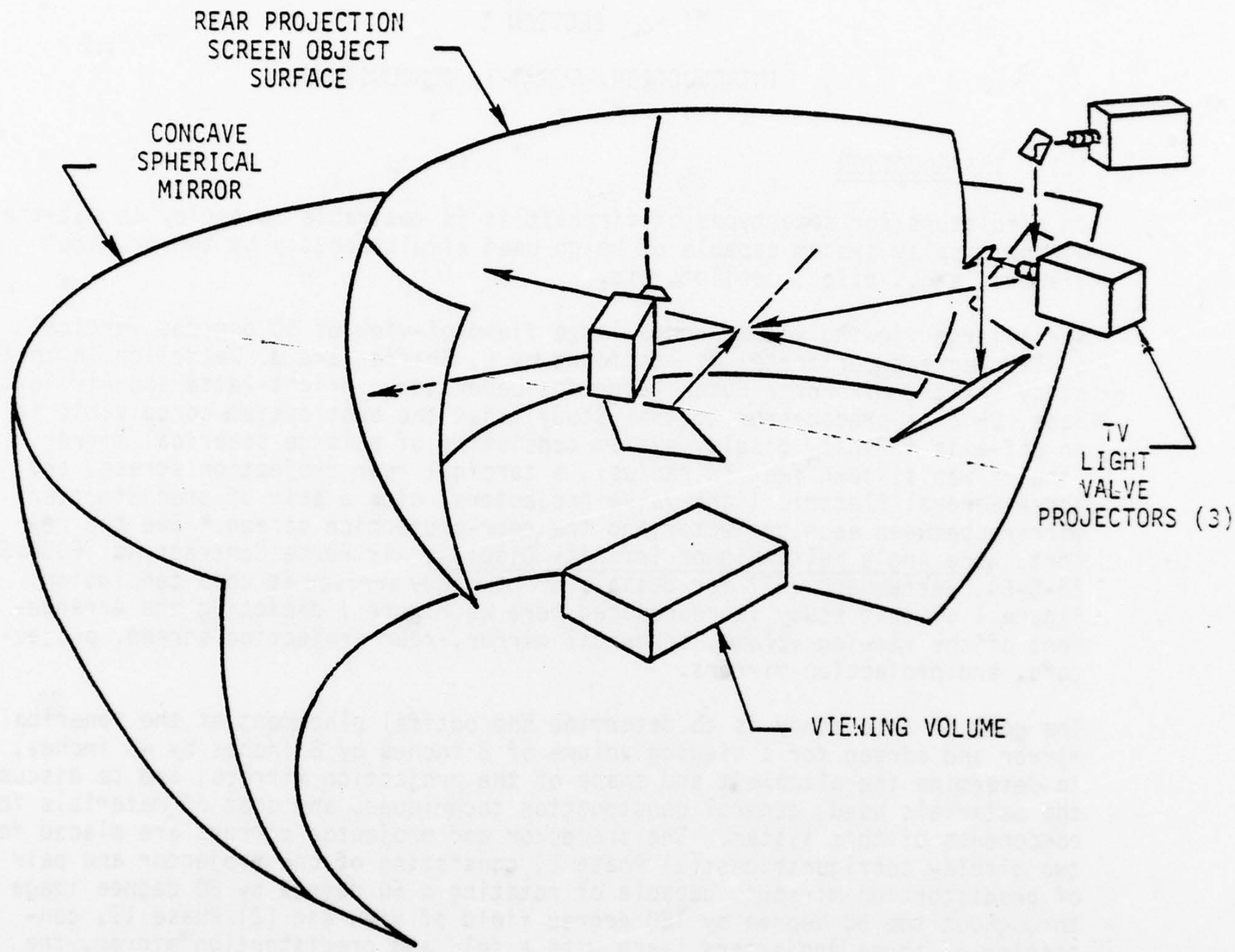


Figure 1. Proposed Wide-Angle, Multi-Viewer, Infinity Display

1.2 SUMMARY

The system was designed to optimize performance with respect to collimation, image swimming with head motion, and distortion. Analysis was made of brightness cross-screen reflectance, and resolution. The construction techniques and types of materials to be used were addressed, and the names of some vendors are given. The analysis resulted in the following optical layout parameters, numbered as per the Statement of Work:

- A - 14 feet
- B - 78.2363 inches
- C - 101.3367 inches
- D - Phase I: 55.36 inches Phase II: 15 inches
- E - Phase I: 30 inches Phase II: 7.5 inches
- F - 23.1004 inches
- G - 10.5 inches
- H - 0.9 inch
- I - 77 inches
- J - 132 inches

See Figure 4 for labelling of parameters A-C and F-J and see Figures 14a and 17a for parameters D and E.

1.3 CONCLUSIONS

All the requirements listed in the original NADC Table 1 requirements were met. Additionally, collimation was kept within +4 milliradians except for little-used or inaccessible portions of the field-of-view, that is those positions that can not be seen in existing cockpits. The same statement is true for distortion which is held to below 3 degrees, or 5 percent of the maximum field height, except for normally unused directions in the field.

Information from vendors confirmed that, in their opinion, the construction of the main components is feasible although it borders on the state of the art in many cases.

Because the design approach contains many good features such as the prospect of a displayed collimated image for a complete cockpit crew that contains no gaps over 180 degree by 60 degree, and less problems than those associated with modular displays, the further pursuit of an optical display of this type is suggested.

SECTION 2

ANALYTIC RESULTS

2.1 OPTICAL SYSTEM DESIGN PARAMETERS AND DISTANCES

2.1.1 BASIC PROCEDURE

The optical system was designed in two stages. The first task was to determine the optimal placement of the viewing volume and rear-projection screens relative to the spherical mirror, and to analyze the placement for collimation, swimming of images, and distortion. Then the placement and shapes of the projection mirrors was determined for Phase I and Phase II.

2.1.2 VIEWING VOLUME, SPHERICAL MIRROR, AND SCREEN PLACEMENT

At the outset the goal was to place the viewing volume and rear projection screen close to those dimensions supplied to us by NADC. Figure 2 shows an elevation view of this portion of the display system, with the viewing volume centered at the point $(0, -y_c, z_c)$. Throughout this study, the x-coordinate is to the left, positive y is up, and positive z is forward. The point (0, h, k) is the center of the circle obtained by intersecting the yz plane with the toroid screen. Initially two systems were defined, one with the exact y_c and z_c given by the Naval Air Development Center, which we'll call the "NADC" case and the other a scaled-down version of the system defined in the Human Resources Laboratory report, which we'll call the "0.8 WAMVID" case. It was found that the viewing volume needed to be moved six inches forward of the exact scaled-down position in the 0.8 WAMVID system in order for the analyzed field of view, 30 degrees above the horizon to 30 degrees below the horizon at that time, to clear the rear projection screen.

For the given placement of the viewing volume in each system, spot diagrams of collimated rays through the viewing volume were constructed and evaluated using the ACCOS V optical design program. These spot diagrams were constructed for azimuths of 0 degrees and 90 degrees and elevation angles of ± 30 degrees, ± 20, ± 10, and 0 degree, where trials were made with aperatures placed in the front, middle, and rear of a 12 inch by 12 inch by 48 inch viewing volume. An ACCOS V program called BFSTAT was used to determine the optimal focus of these spots, the locus of which defines the surface of the rear-projection screen.

a. NADC Case

The center of the viewing volume was placed 84 inches below and 42 inches in front of the center of the spherical mirror. See Figure 3 for a layout of the system. The locus of the optimum focus points are plotted for the 0 degree azimuth and 90 degree azimuth trials. Remembering that the rear projection screen must be symmetric with respect to rotation about the y-axis, one must choose for each elevation angle which point will define the rear projection screen surface. The 90 degree azimuth placement cannot be used since the 30 degrees upward field of view angle is obstructed by the

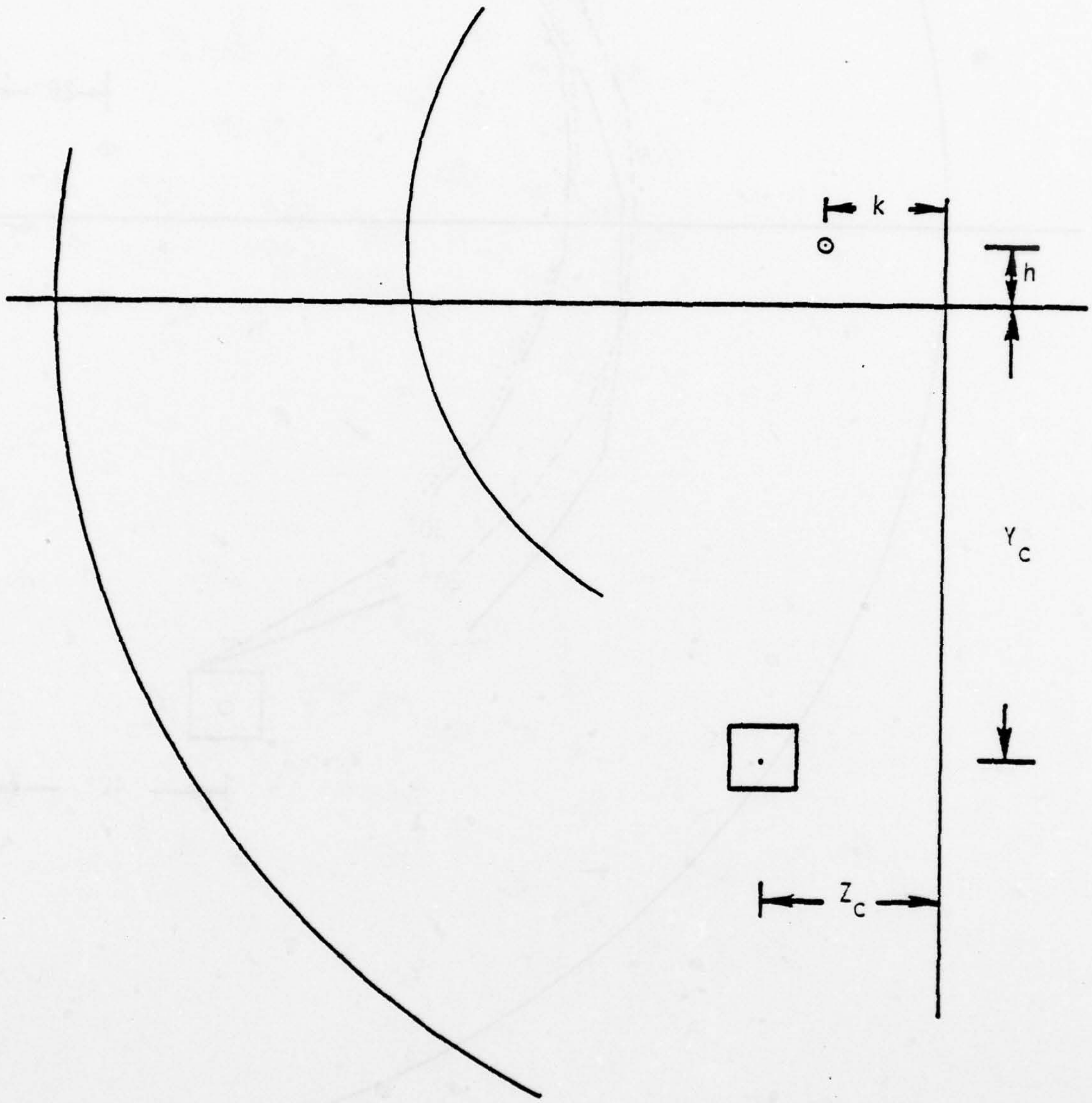
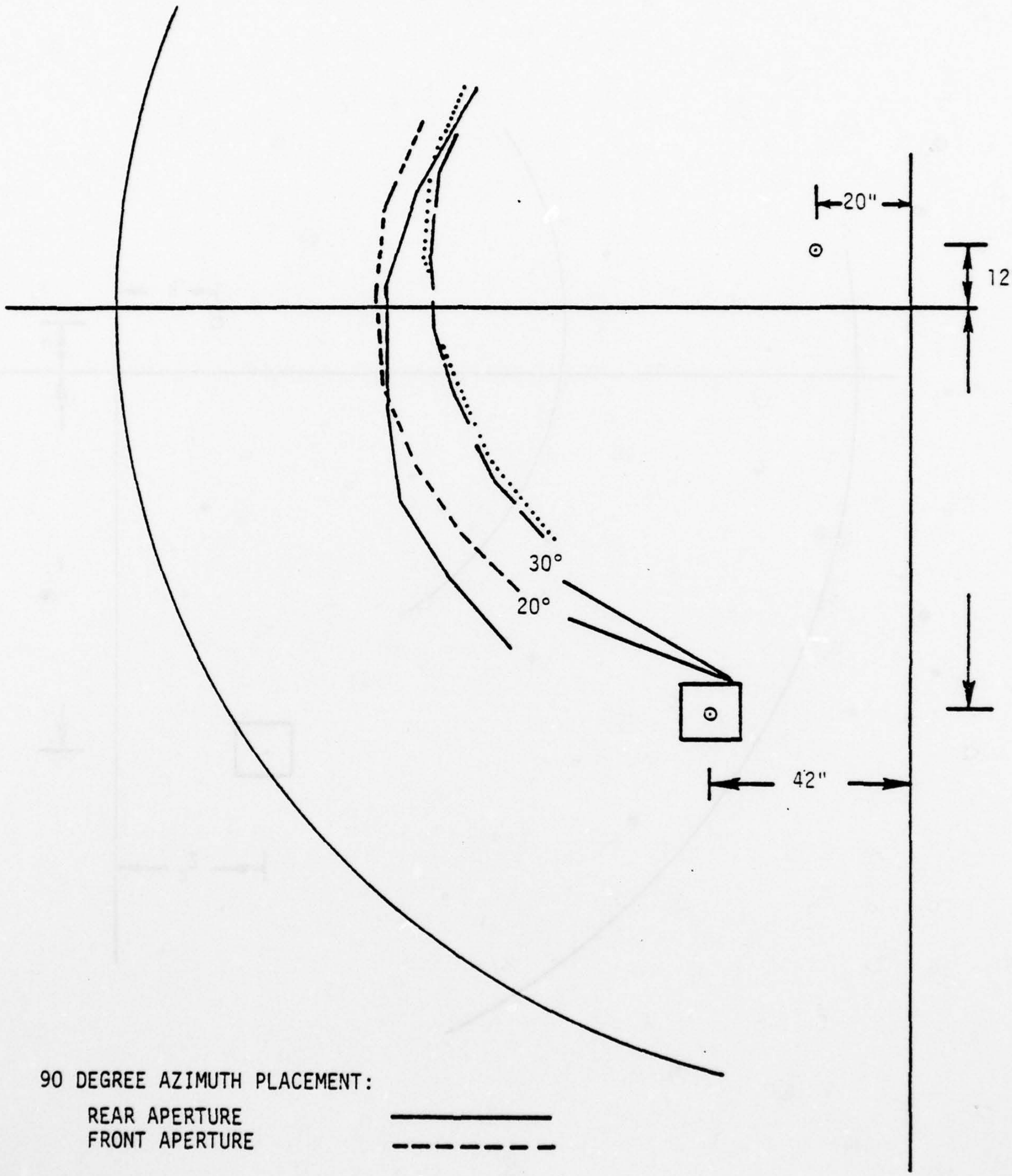


Figure 2. Elevation View of the System



90 DEGREE AZIMUTH PLACEMENT:

REAR APERTURE

FRONT APERTURE

0 DEGREE AZIMUTH PLACEMENT

REAR APERTURE

FRONT APERTURE

Figure 3. "NADC" Case, Elevation View

screen. In fact, this angle is barely cleared by the 0 degree azimuth-defined screen position. Therefore, the screen defined by the 0 degree azimuth position is used. Since the screen is a toroid, its cross section is a circle. Its center and radius were determined using the ±30 and 0 degree elevation angle positions for AZ=0.

b. 0.8 WAMVID Case

This case is not shown, but is similar to the NADC case. In this case, the center of the viewing volume was placed 78.4 inches below and 30 inches in front of the center of the spherical mirror. Again the 0 degree azimuth-defined focus points needs to be used to define the screen surface, due to field-of-view considerations.

c. Comparison Between the 0.8 WAMVID and NADC Cases

The computer program LO, modified only slightly from the version used in the study for the Air Force Human Resources Laboratory, was used to analyze the collimation, distortion, and swimming effects of the systems. The "swimming" effects of the two systems, i.e., the changes in the azimuth and elevation of a screen point as the viewer moves are seen in Tables 1 and 2. Especially disturbing is the drop of several degrees in elevation angle as the viewer drops his eyepoint ten inches. A comparison of the two tables reveals that the 0.8 WAMVID case performed slightly better in the more troublesome parts of the field of view, so it was selected at this stage of the study.

d. 14-Foot WAMVID Case

Several steps have been taken to improve the performance of the 0.8 WAMVID case. First of all an increase in the radius of the system improves the performance within a given sized viewing volume. Especially striking is the improvement in the performance of the system as one moves the viewing volume closer to the center of the sphere. Additional movement toward the center of the sphere is possible if the field of view used is +20 degrees elevation to -40 degrees elevation. The system so defined is shown in Figure 4.

In the following pages are the results of the distortion, swimming, and collimation analysis for the 14-foot WAMVID system. Figure 5 shows the various eye positions in an 8-inch by 8-inch by 48-inch viewing volume for which the distortion analysis was performed on the copilot's portion of the viewing volume. The pilot's view is simply a mirror image of the copilot's view. The positions are labelled by up to 3 letters: The first is F for the front of the viewing volume or B for the rear. The second is U for the upper portion or L for the lower. The third is R for the right of the copilot's portion of the viewing volume or L for the left. The position C is the center position and FE is the flight engineer position behind the center of the viewing volume.

In Figures 6 through 11 are shown the distortion plots for positions FUR, FUL, BUR, FLR, C, and FE respectively. On Figures 7, 8, 9 are also shown the FUR distortion plot in dashed lines for the evaluation of swimming effects. Note

Table 1. "Swimming" Analysis for "NADC" Case

Ideal Azimuth	Ideal Elevation	Azumuth (A) Elevation (E)	Back of Viewing Volume					Front of Viewing Volume				
			X Y -21 -79	X Y -21 -89	X Y 0 -84	X Y 21 -79	X Y 21 -89	X Y -21 -79	X Y -21 -89	X Y 0 -84	X Y 21 -79	X Y 21 -89
0°	30	A	1.3	0.1	0	1.3	-0.1	0	-1.5	0	0	1.5
		E	32.5	28.1	32.1	32.5	28.1	30	21.2	30	30	21.2
0°	0	A	0.6	-0.2	0	-0.6	0.2	0.6	-0.1	0	-0.6	0.1
		E	0.4	-2.5	0	0.4	-2.5	0.4	-2.3	0	0.4	-2.3
0°	-30	A	0	0.3	0	0	0.3	0	0.1	0	0	0.1
		E	-30	-31.4	-30	-30	-31.4	-30	-30.8	-30	-30	-30.8
90°	30	A	4.0	3.7	3.4	2.7	1.1	5.0	4.4	3.7	2.3	Routine Did Not Converge
		E	33.4	33.7	33.6	32.8	30.2	33.0	33.1	32.6	31.1	
90°	0	A	0.2	-4.7	-0.7	0.4	-1.4	Routine Did Not Converge	-15.6	-3.2	-0.9	-3.6
		E	-1.3	-13.3	-3.3	-1.0	-5.2		-28.0	-7.3	-3.2	-8.4
90°	-30	A	-4.9	-7.0	-2.9	-1.1	-1.9	-8.8	-11.6	-5.4	-2.5	-3.6
		E	-38.8	-42.9	-35.4	-32.1	-33.5	-41.2	-45.1	-36.9	-33.1	-34.6

Table 2. "Swimming" Analysis for "0.8 WAMVID" Case

Ideal Azimuth	Ideal Elevation	Azumuth (A) / Elevation (E)	Back of Viewing Volume					Front of Viewing Volume				
			X Y -21 -73.4	X Y -21 -83.4	X Y 0 -78.4	X Y 21 -73.4	X Y 21 -83.4	X Y -21 -73.4	X Y -21 -83.4	X Y 0 -78.4	X Y 21 -73.4	X Y 21 -83.4
0°	30°	A	1.4	-0.0	0	-1.4	0.0	0	-2.2	0	0	Routine Failed to Converge
		E	32.3	28.0	32.1	32.3	28.0	30	18.9	30	30	
0°	0°	A	0.8	-0.2	0	-0.8	0.2	0.8	-0.1	0	-0.8	0.1
		E	1.0	-2.6	0	1.0	-2.6	0.9	-2.3	0	0.9	-2.3
0°	-30°	A	0	-0.5	0	0	0.5	0	0	0	0	0
		E	-30	-31.3	-30	-30	-31.3	-30	-30	-30	-30	-30
90°	30°	A	2.8	2.5	2.2	1.6	0.2	3.9	3.4	2.8	1.6	Routine Failed to Converge
		E	33.4	33.6	33.4	32.4	28.6	33.0	33.1	32.5	30.9	
90°	0°	A	0.9	Routine Failed to Converge	0.3	0.9	-0.3	0.4	-9.5	-0.7	0.6	-1.6
		E	0.9		-0.9	0.8	-3.1	-0.9	-22.7	-3.5	-0.8	-5.6
90°	30°	A	-2.7	-4.4	-1.5	0	-0.8	-5.6	-8.3	-3.1	-0.9	-1.9
		E	-36.8	-41.5	-33.5	-30	-31.8	-38.9	-43.8	-34.8	-31.3	-32.8

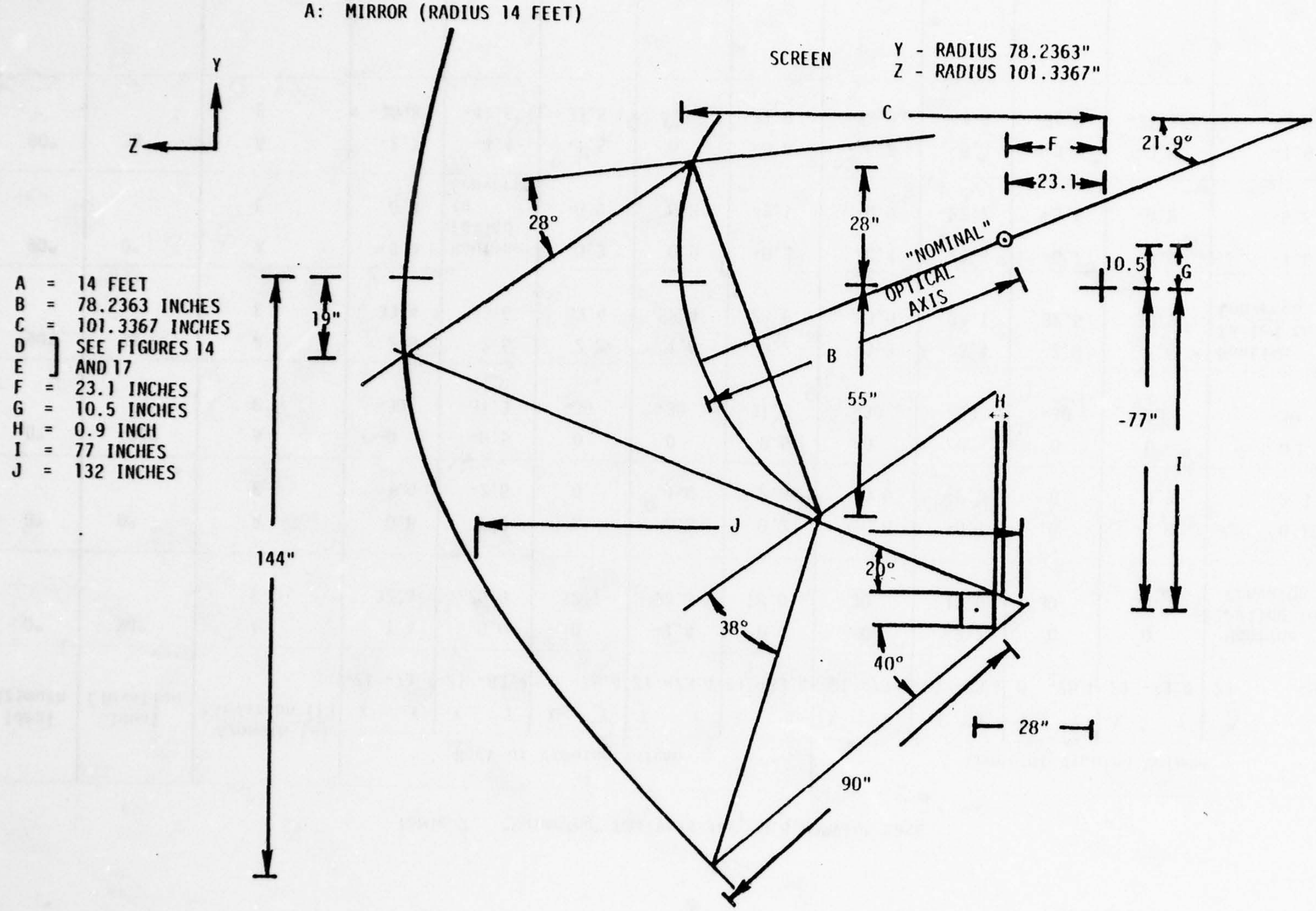


Figure 4. "14-foot WAMVID" Case

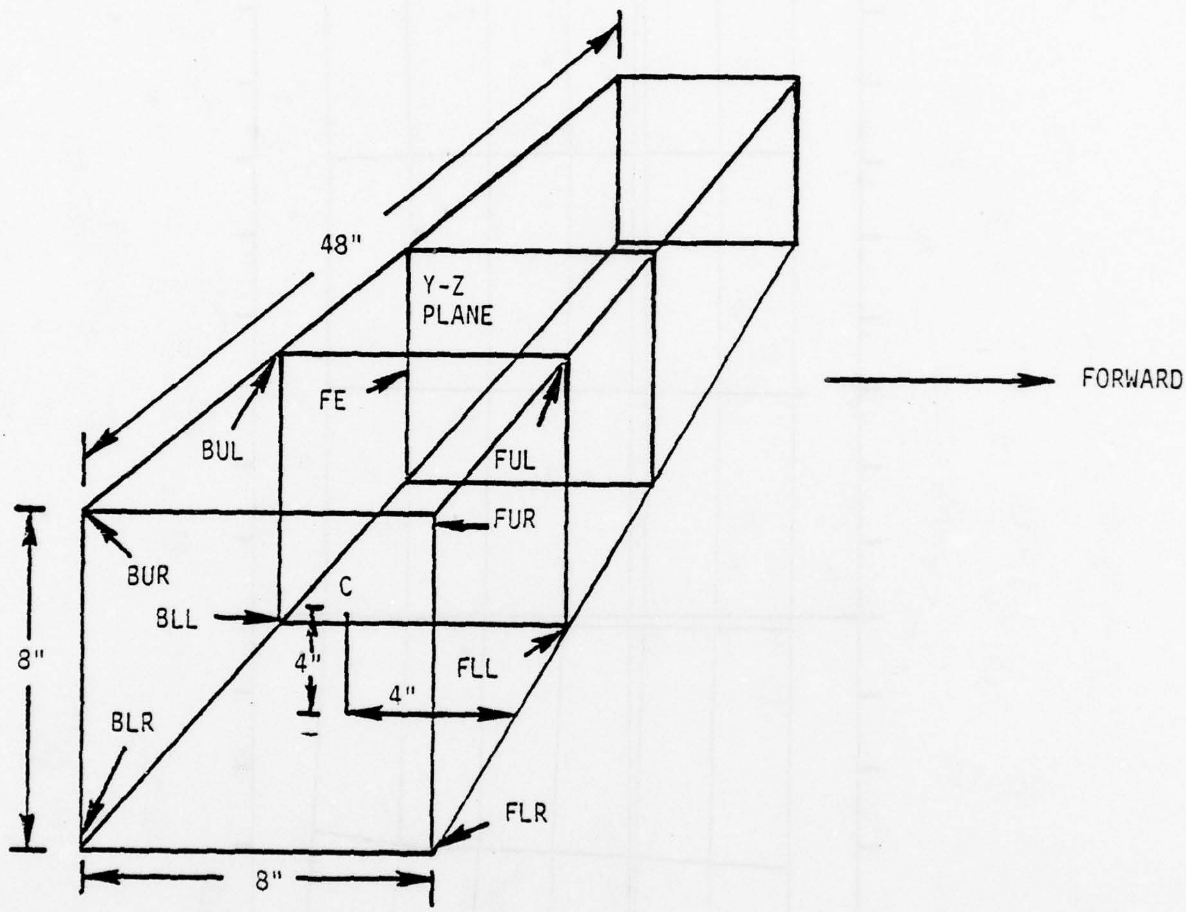


Figure 5. Side View Showing Analyzed Viewpoints

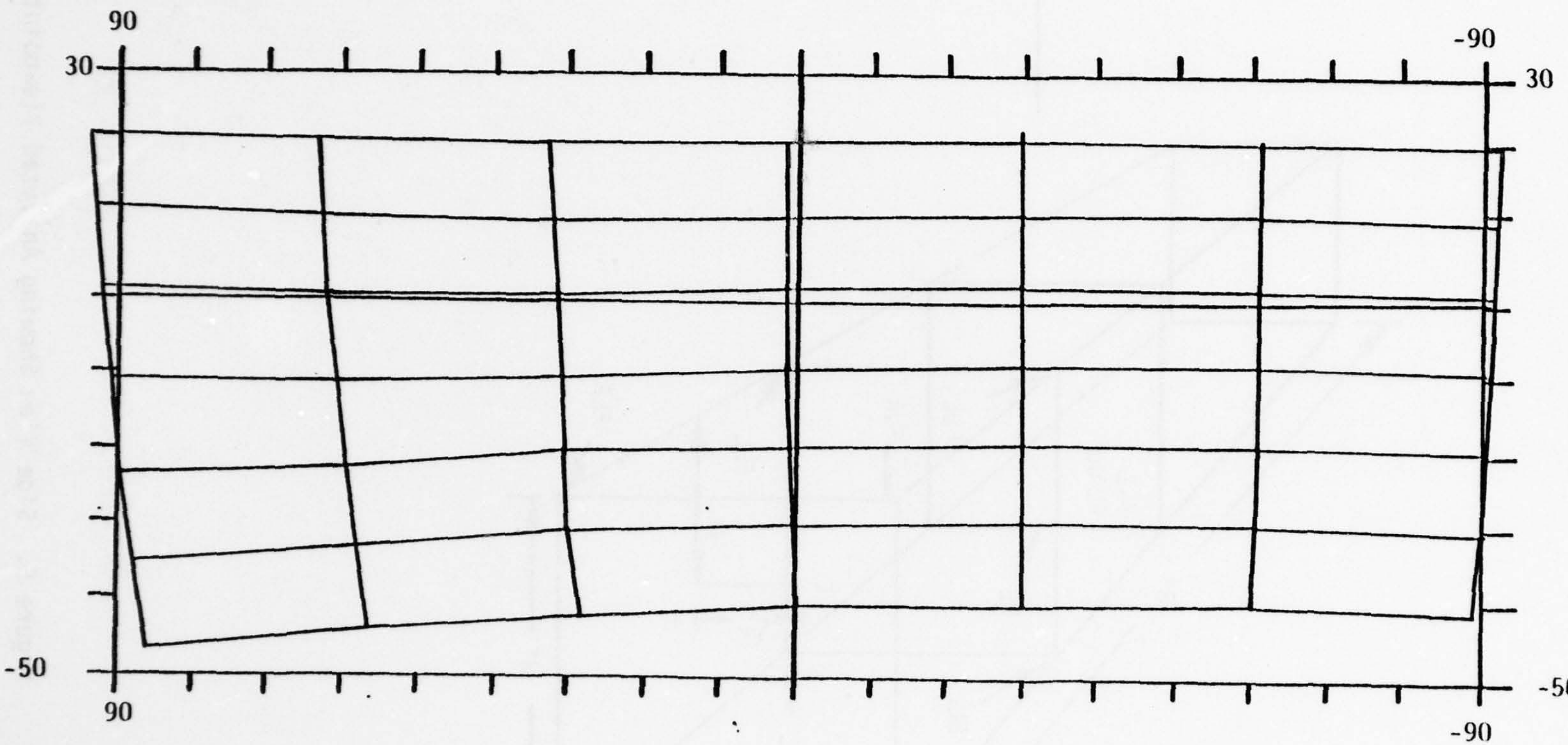


Figure 6. Distortion Plot for Position FUR

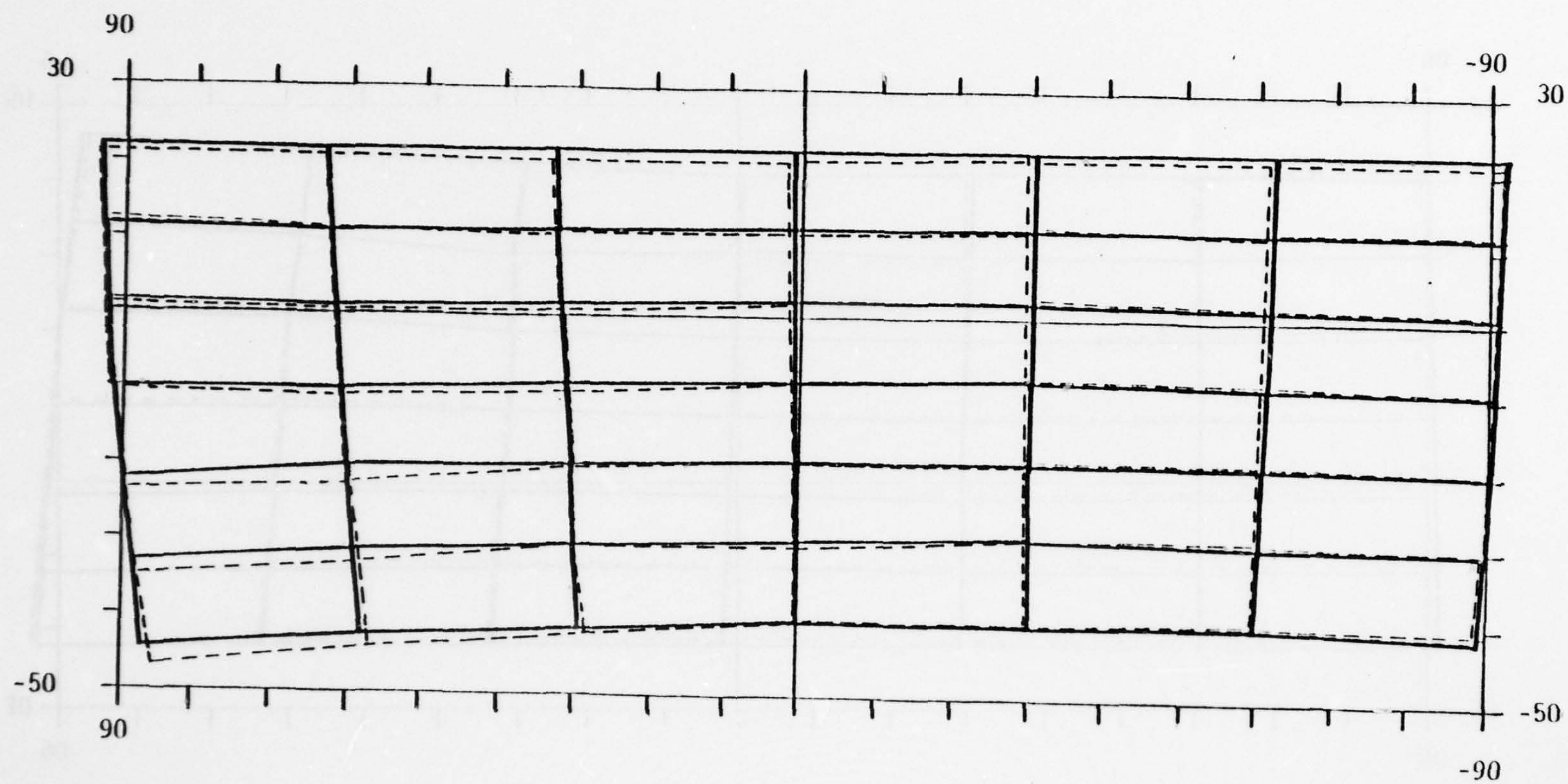


Figure 7. Distoriton Plot for Position FUL

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DESIGN OF AN OFF-AXIS WIDE FIELD-OF-VIEW VISUAL DISPLAY SYSTEM --ETC(U)
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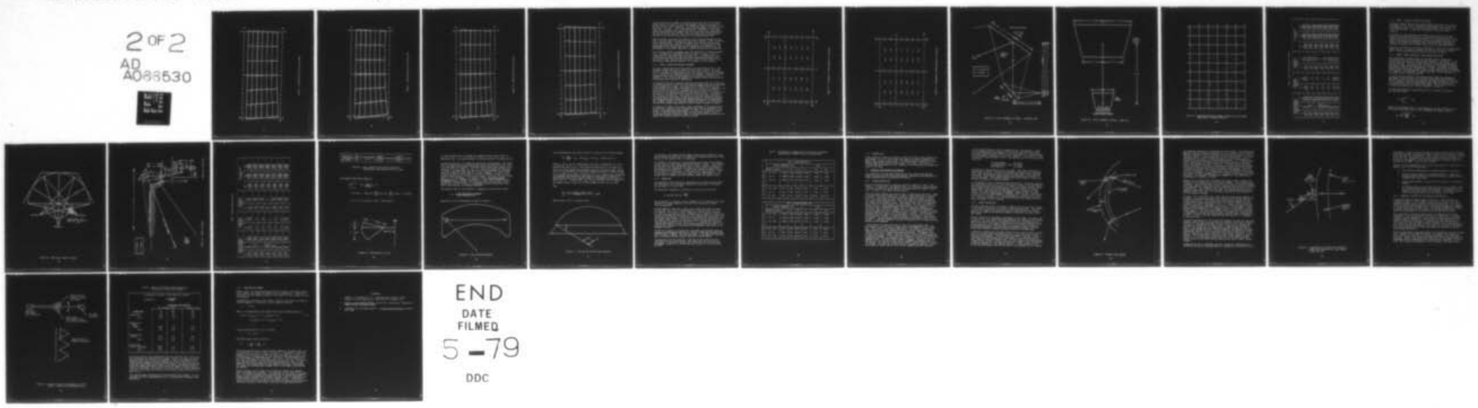

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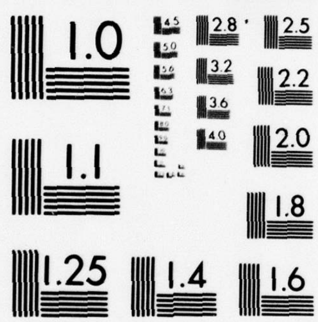

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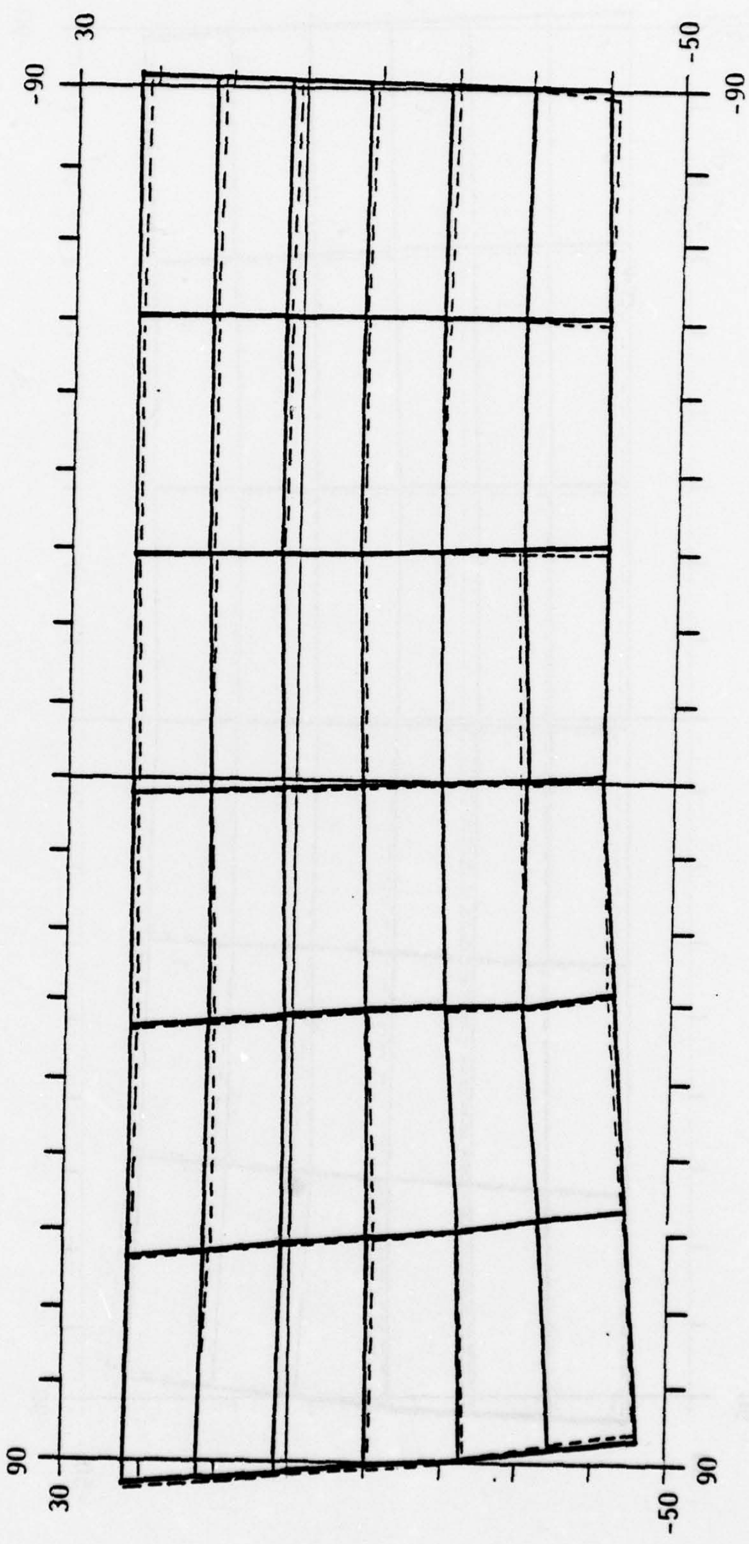

Figure 8. Distortion Plot for Position BUR

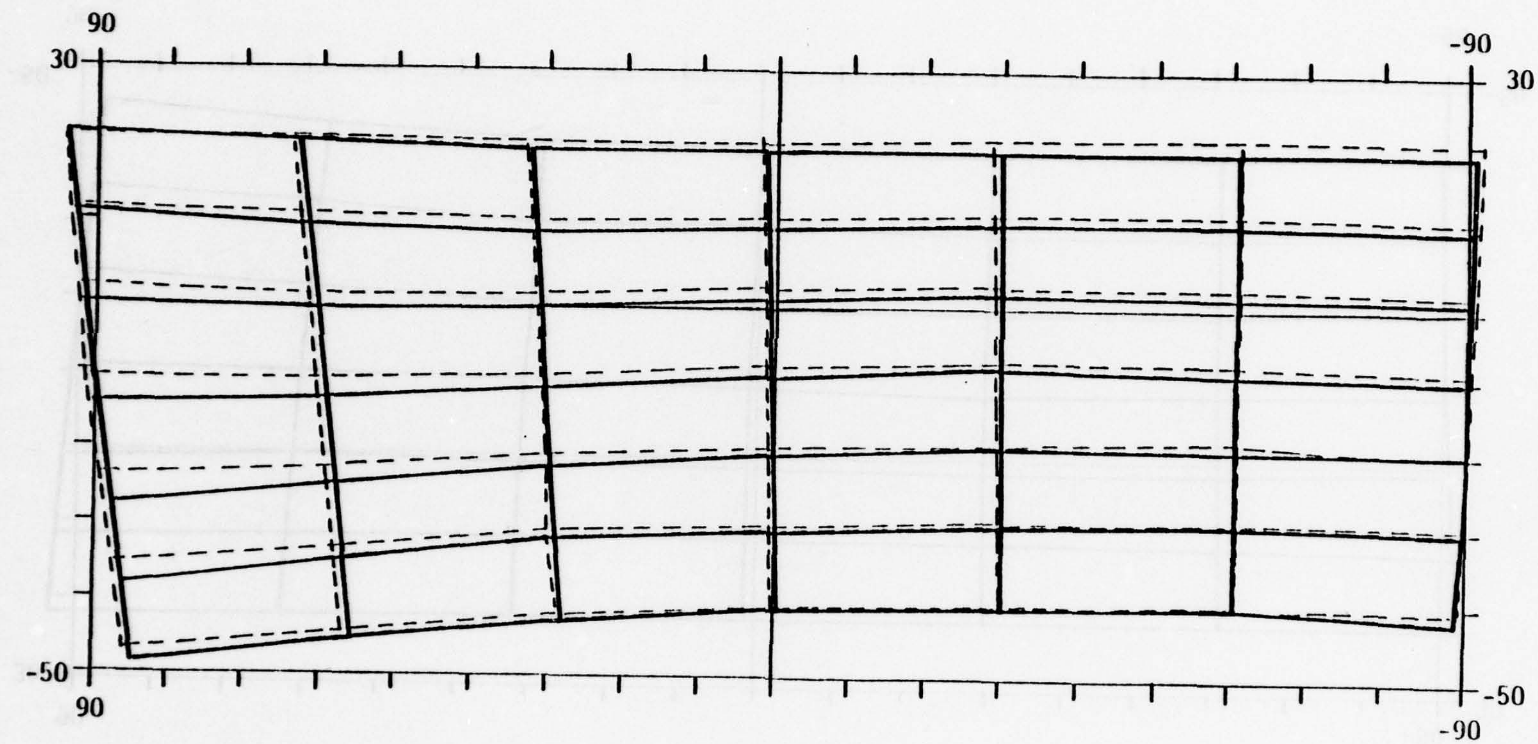

Figure 9. Distortion Plot for Position FLR

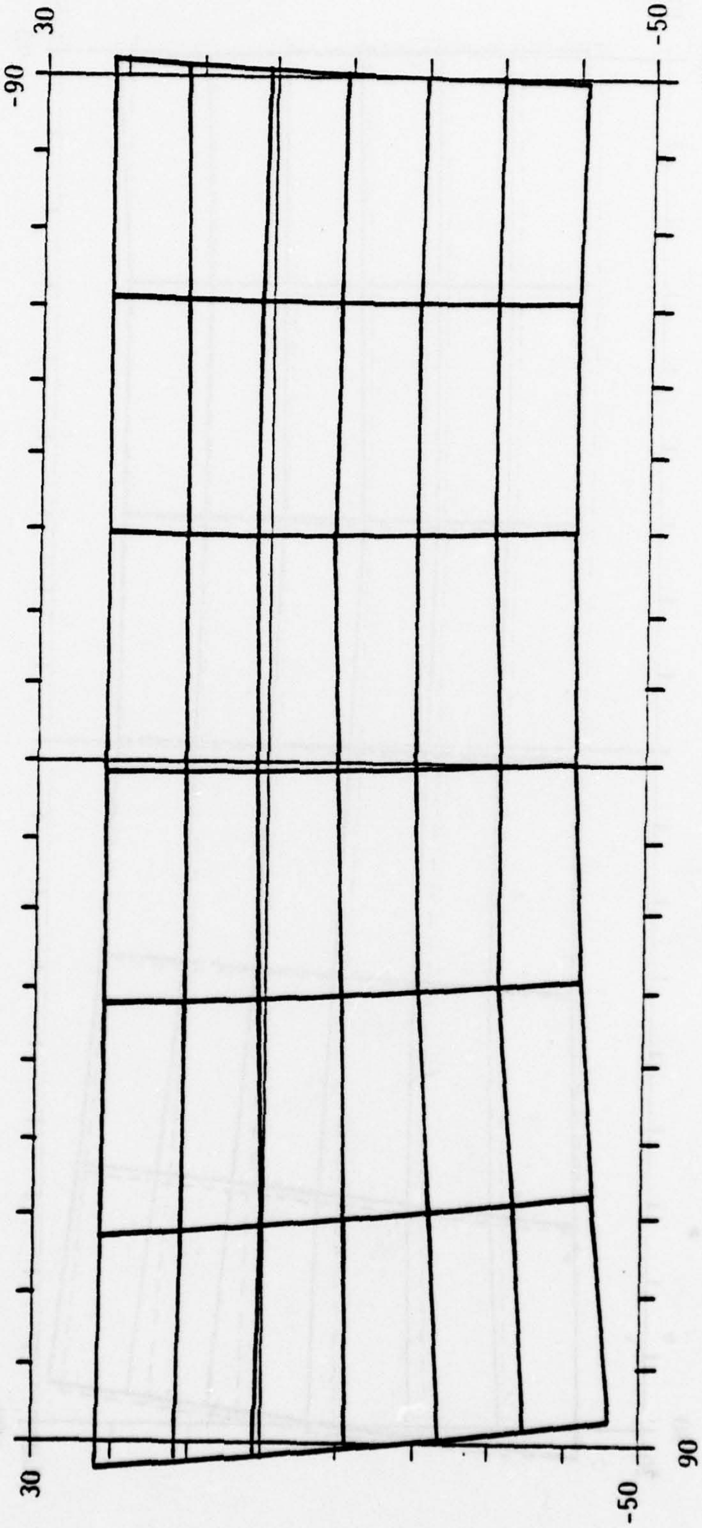

Figure 10. Distortion Plot for Position C

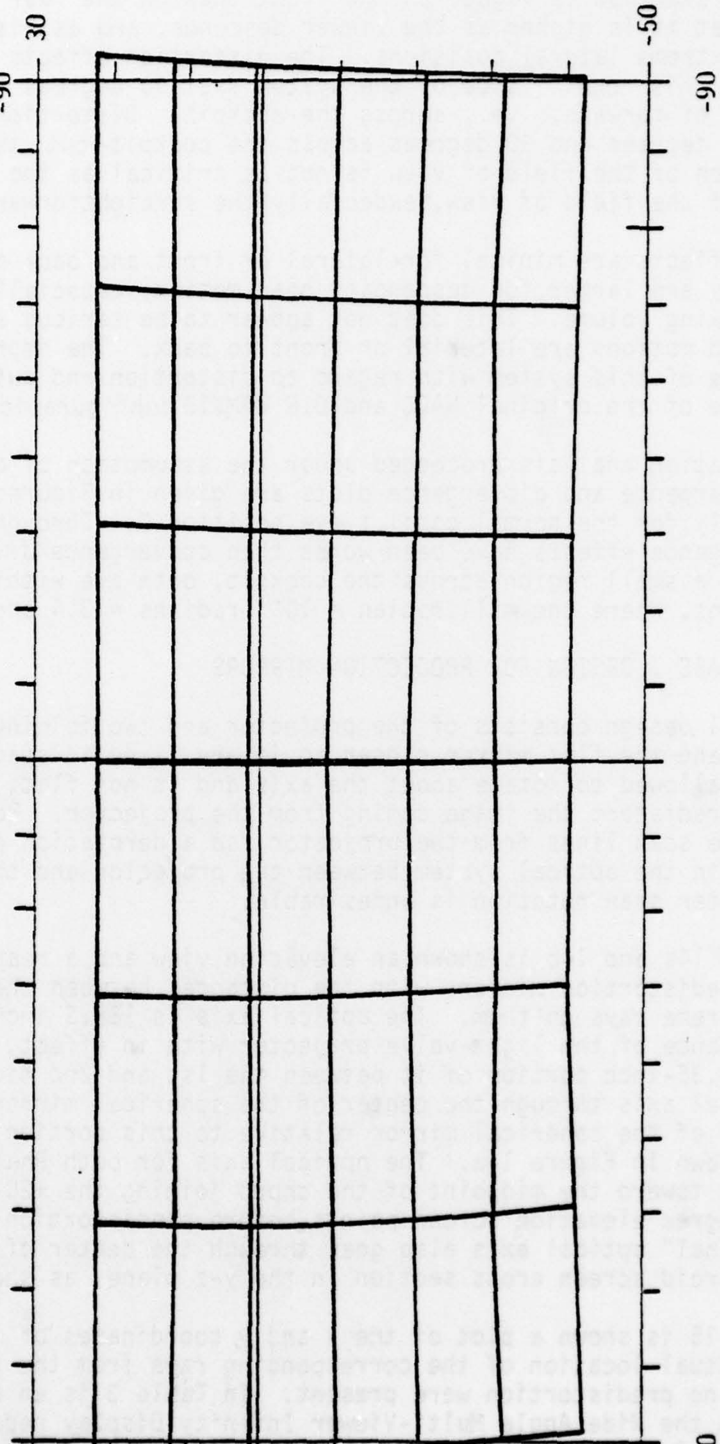

Figure 11. Distoriton Plot for Position FE

that the distortion is higher on the front than on the rear of the viewing volume, that it is higher as the viewer descends, and as his eye moves to the more extreme lateral positions. The distortion effects are small for the copilot on his own side of the system from 90 degrees to a 30 degree angle left of forward, i.e., across the cockpit. Distortion is much worse between 30 degrees and 90 degrees across the cockpit—but the performance of this portion of the field of view is not as critical as the performance of the rest of the field of view, expecially the straightforward area.

Swimming effects are minimal for lateral or front and back movement of the head. They are larger for descending head motion, especially near the bottom of the viewing volume. This does not appear to be serious since the most natual head motions are laterial or front to back. The improvement of the performance of this system with regard to distortion and swimming over the performance of the original NADC and 0.8 WAMVID configurations is noteworthy.

The collimation analysis proceeded under the assumption of a 70mm eye separation. Divergence and dipvergence plots are given in Figures 12 and 13 respectively for the normal copilot eye position C. Throughout the study, the dipvergence effects have been worse than convergence/divergence, but except for a small region across the cockpit, both are within the limits ± 4 milliradians, where one milliradian = 10^{-3} radians = 3.4 arc minutes.

2.1.3 PHASE I DESIGN FOR PROJECTION MIRRORS

The Phase 1 design consists of the projector and two folding mirrors. The projector and the flat mirror closer to it are fixed in space. The other mirror is allowed to rotate about the axis and is not flat, but has curvature to it to predistort the image coming from the projector. Rotating this mirror rotates the scan lines from the projector, so a derotation prism will be necessary in the optical system between the projector and the rotating mirror if the raster scan rotation is undesirable.

In Figures 14a and 14b is shown an elevation view and a rear view of the folding and predistortion mirrors with the distances between them and the positions of the extreme rays on them. The optical axis is 188.5 inches long (the throw distance of the light-valve projector with in effect, a 2x adaptor on it), and the 55.36-inch portion of it between the 1st and 2nd mirrors follows the vertical axis through the center of the spherical mirror. The position of the center of the spherical mirror relative to this portion of the optical axis is shown in Figure 14a. The optical axis for both Phase I and Phase II is pointed toward the midpoint of the chord joining the +20-degree elevation and -40-degree elevation screen points before predistortion is implemented. This "nominal" optical axis also goes through the center of the circle defining the toroid screen cross section in the y-z plane, as shown in Figure 4.

In Figure 15 is shown a plot of the x and y coordinates of the target points and the actual location of the corresponding rays from the projector on the screen if no predistortion were present. In Table 3 is an analysis similar to that in the Wide Angle Multi-Viewer Infinity Display report to the Air Force Human Resources Laboratory, page 97, giving the direction cosines of the normals at the given points on the mirror surface.

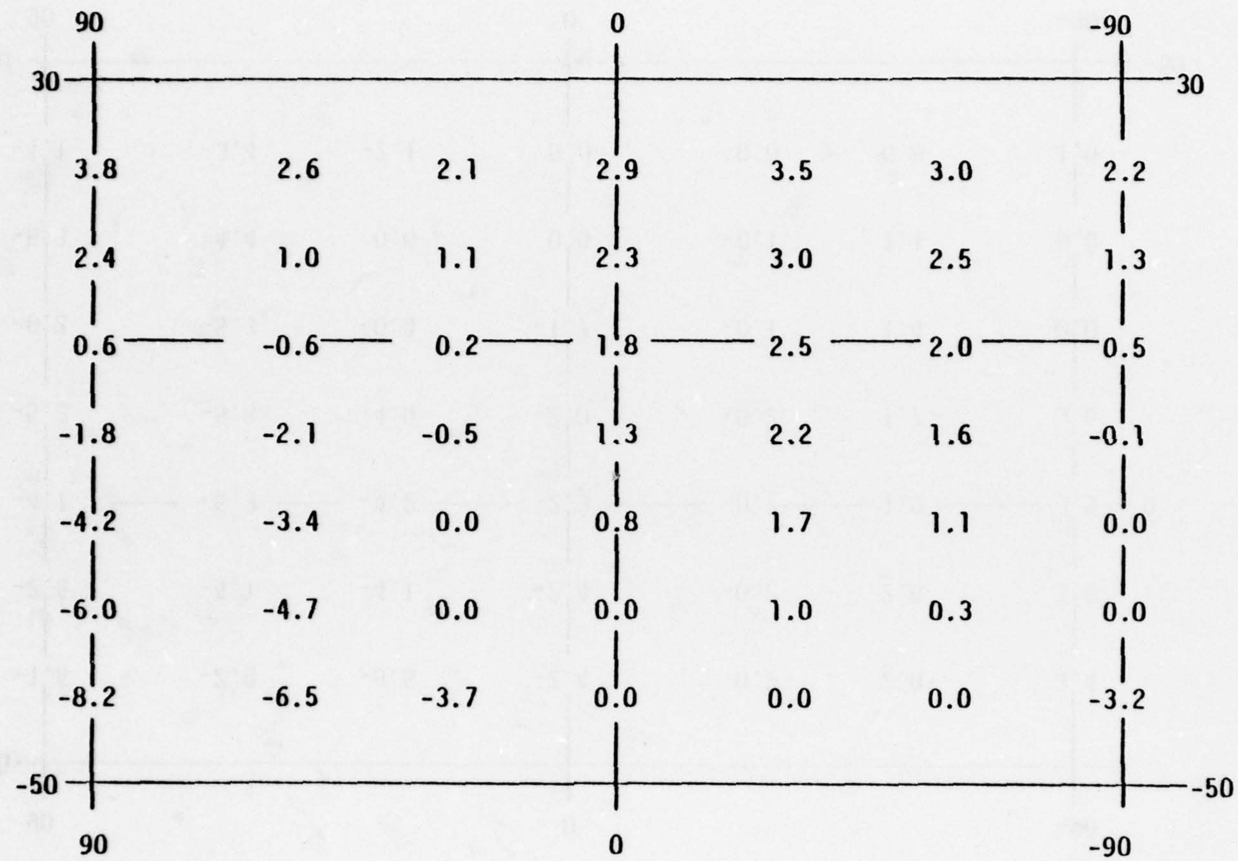

Figure 12. Divergence in Milliradians at Position C

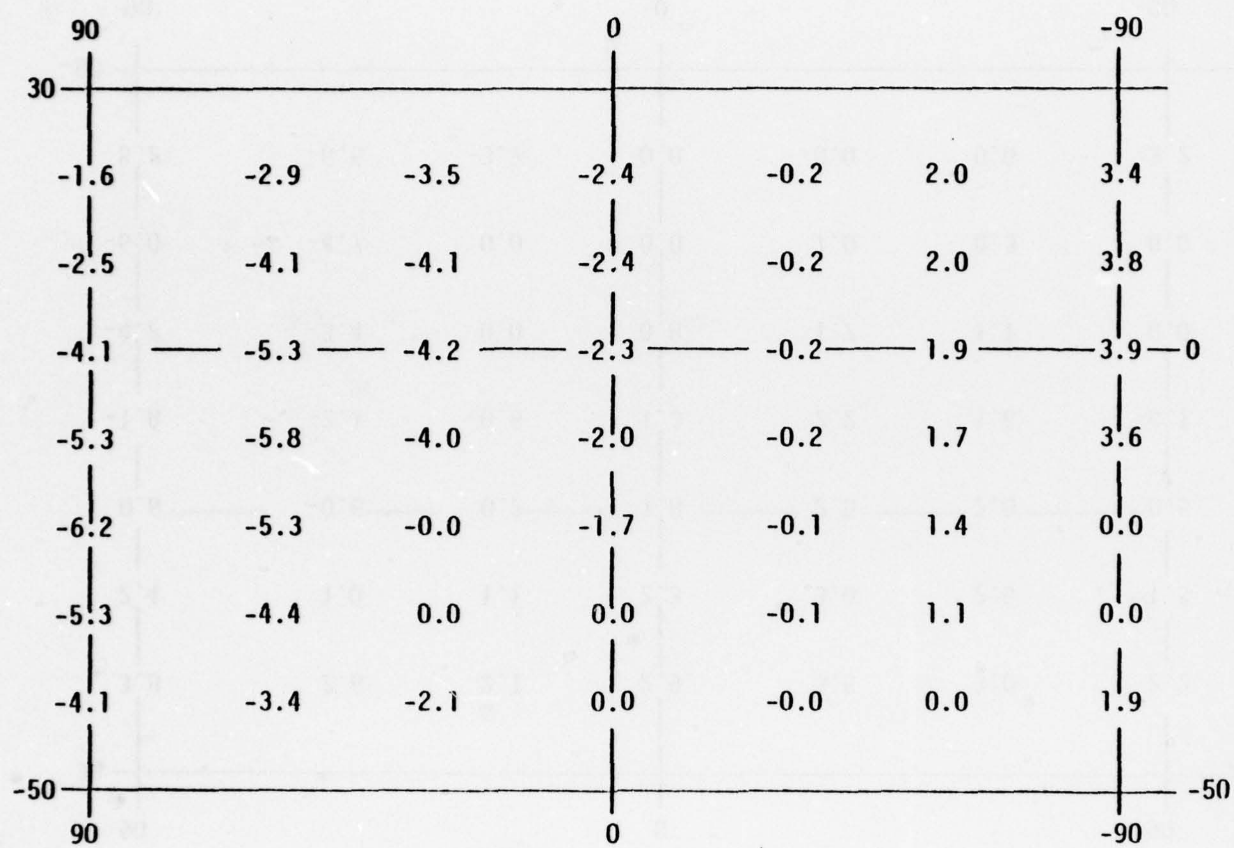

Figure 13. Dipvergence in Milliradians at Position C

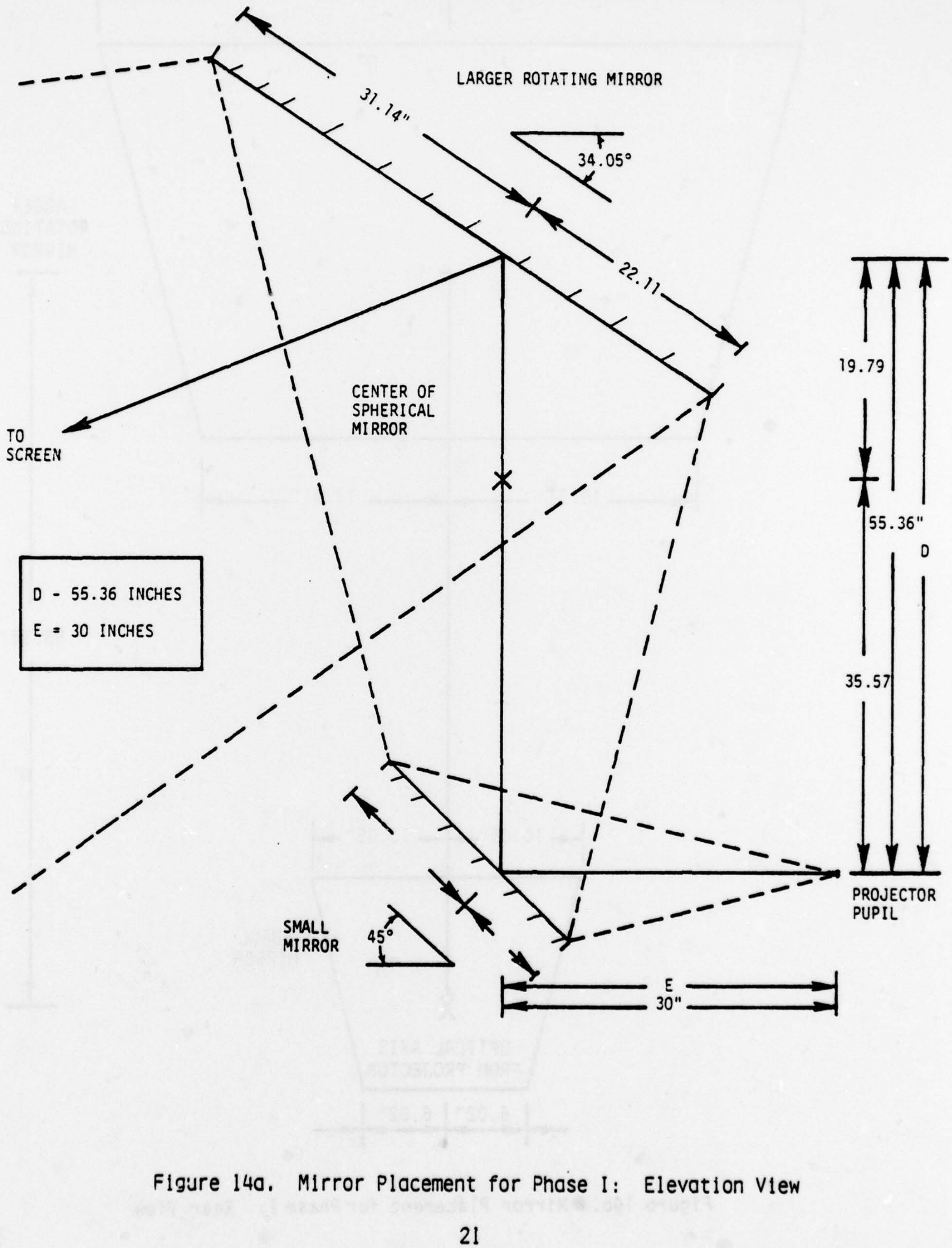

Figure 14a. Mirror Placement for Phase I: Elevation View

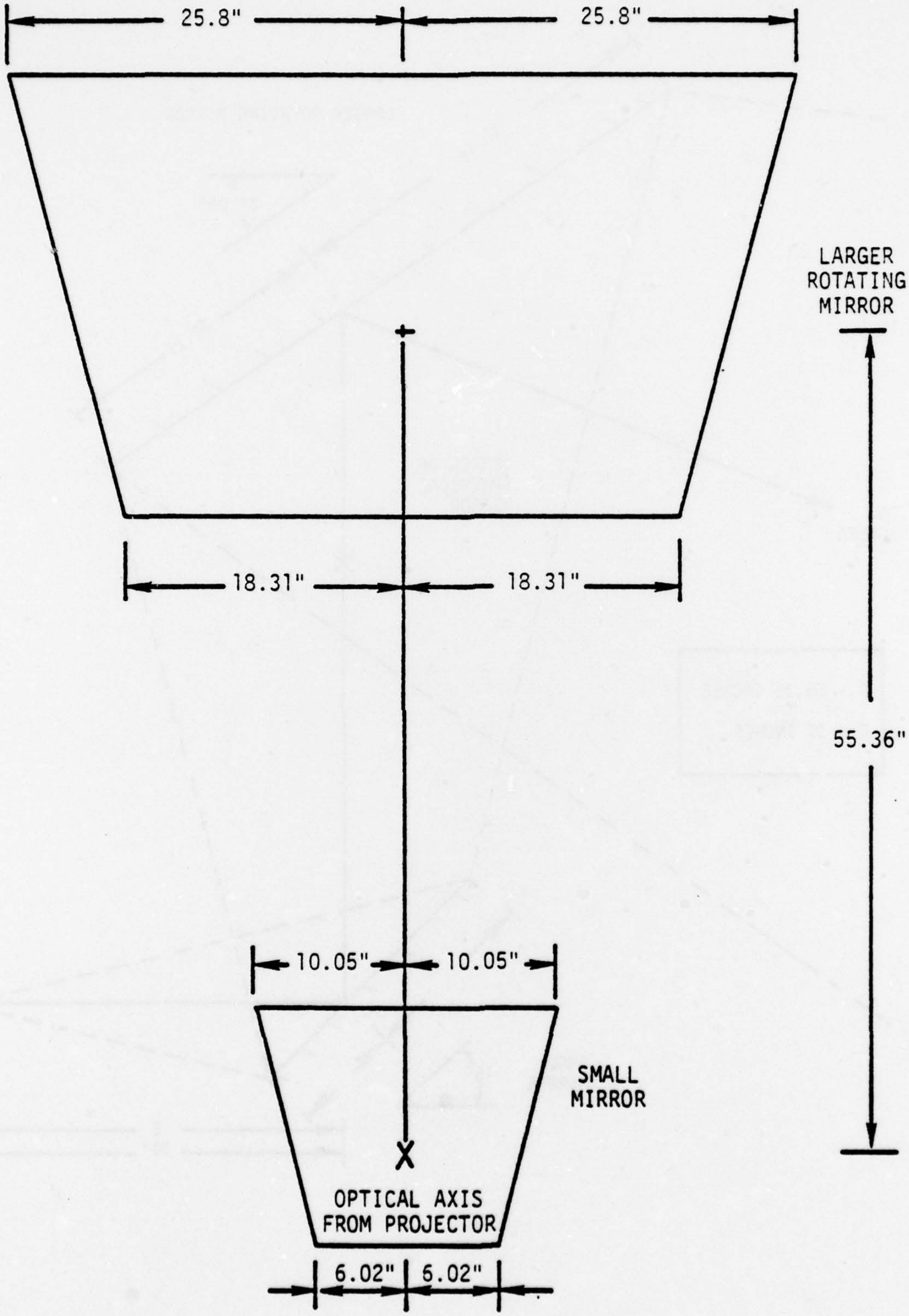

Figure 14b. Mirror Placement for Phase I: Rear View

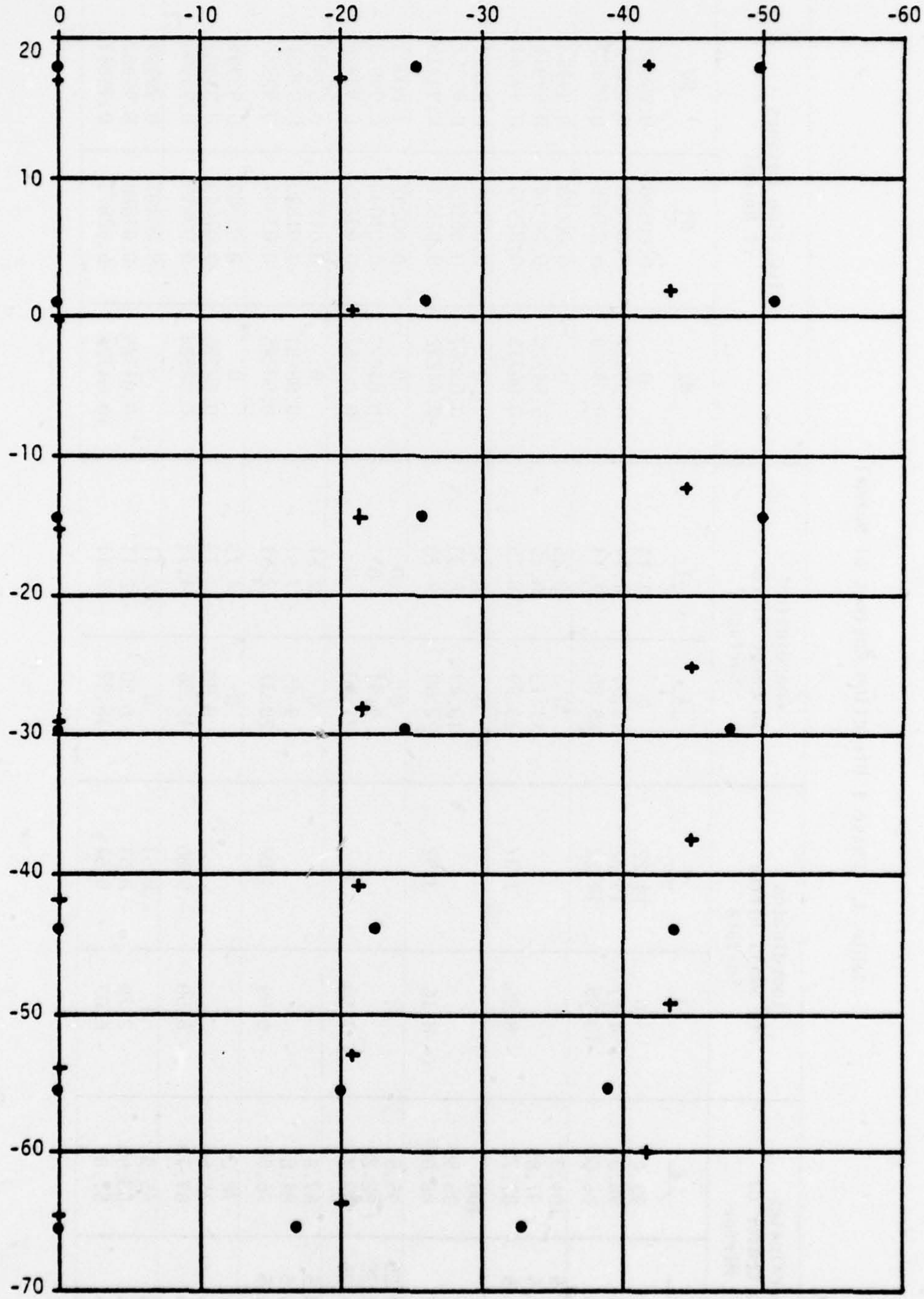

Figure 15. Predistortion Plot for Phase I Relative to 10.5 Inches Above Center of Spherical Mirror

Table 3. Phase I Direction Cosines of Normal

Screen Coordinates Relative to Center of Spherical Mirror			Coordinates in Small Mirror Surface		Coordinates in Large Mirror Surface		Direction Cosines of Normal		
X	Y	Z	X	Y	X	Y	NX	NY	NZ
0	28	99.4	0	14.22	0	31.14	0	0.00580	0.99998
-25.73	28	96.01	- 4.67	14.22	-11.97	31.14	-0.05957	-0.00400	0.99822
-49.7	28	86.08	-10.05	14.22	-25.80	31.14	-0.09969	-0.03105	0.99453
0	11.5	101.3	-	-	0	18.25	0	0.00686	0.99998
-26.22	11.5	97.85	-	-	-11.13	18.25	-0.04220	-0.00164	0.99911
-50.7	11.5	87.73	- 8.95	7.97	-23.99	18.25	-0.06715	-0.02576	0.99741
0	- 4	100	-	-	0	8.33	0	0.00456	0.99999
-25.88	- 4	95.59	-	-	-10.49	8.33	-0,03067	-0.00503	0.99952
-50.0	- 4	86.08	- 8.16	3.52	-22.60	8.33	-0.04272	-0.02601	0.99875
0	-19.25	95.5	-	-	0	0	0	-0.00292	1.00000
-24.71	-19.25	92.25	-	-	- 9.94	0	-0.01823	-0.01038	0.99978
-47.8	-19.25	82.71	- 7.53	0	-21.43	0	-0.02062	-0.03235	0.99926
0	-33.5	87.8	-	-	0	- 7.51	0	-0.01121	0.99994
-22.72	-33.5	84.81	-	-	- 9.45	- 7.51	-0.00681	-0.01830	0.99981
-43.9	-33.5	76.04	- 6.99	- 3.02	-20.37	- 7.51	0.00246	-0.03934	0.99922
0	-45	78.2	-	-	0	-14.73	0	-0.00989	0.99995
-20.24	-45	75.54	-	-	- 8.98	-14.73	0.00390	-0.01649	0.99986
-39.1	-45	67.72	- 6.50	- 5.80	-19.36	-14.73	0.02388	-0.03619	0.99906
0	-55	65.9	0	- 8.51	0	-22.11	0	-0.00481	0.99999
-17.06	-55	63.65	- 2.79	- 8.51	- 8.50	-22.11	-0.01569	-0.01080	0.99982
-33	-55	57.07	- 6.02	- 8.51	-18.32	-22.11	+0.04728	-0.02875	0.99847

2.1.4 PHASE II DESIGN FOR PROJECTION MIRRORS

The Phase II design requires that three projectors and mirrors be placed to simultaneously fill the full 60 degrees by 180 degrees field-of-view. The light beams from each mirror should not be obstructed by any other mirror in the entire system. A plan view of the Phase II set up is shown in Figure 16.

In Figures 17 a and b are shown an elevation view and rear view of the Phase II predistortion mirror set up. Also shown in the elevation view is the position of the light beam from Projector 1 in the plane parallel to the "nominal" optical axis of projector 3 and passing through the extreme far corner of the larger predistortion mirror. Since the light beam does not intersect the mirrors in this plane, there will be no light obstruction.

The plot in Figure 15 is very close to the Phase II results for the uncorrected image location. Of course, the target locations are the same for Phases I and II. The direction cosines for Phase II are shown in Table 4.

2.1.5 FRESNEL PRISMS, BRIGHTNESS, CROSS-SCREEN REFLECTANCE

The introduction of Fresnel prisms into the design would increase the efficiency of the use of the light from the projector in the system. It also allows higher gain screens to be used since effectively smaller bend angles would be required. This would reduce the amount of cross-screen reflectance and hence increase the contrast ratio of the screen. The Fresnel prisms are not, however, without their disadvantages. The main problem with the Fresnel prisms is that they cannot be made in sheets larger than 18 inches by 18 inches and, therefore, a large number of seams is required. Analysis was made of the system to see if they are required.

A simplified block diagram of the system from the light-valve projector to the viewer is shown in Figure 18. With 500 lumens output from the General Electric color LV projector, the brightness the viewer sees must be a minimum of 5 ft.-lamberts. With the transmission losses shown in Figure 18, the illumination falling on the screen is 289 lumens. The area of the section of the toroid screen to be lit by one projector is 63.227 ft^2.

This area was obtained by treating the toroid as a surface of revolution and using the formula

$$S = 2\pi \int_{x=a}^{x=b} y\,ds$$

where S is the surface area, y is the function of x giving a profile of the curve before revolution, and ds is the incremental arc-length, given by

$$ds = \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\ dx$$

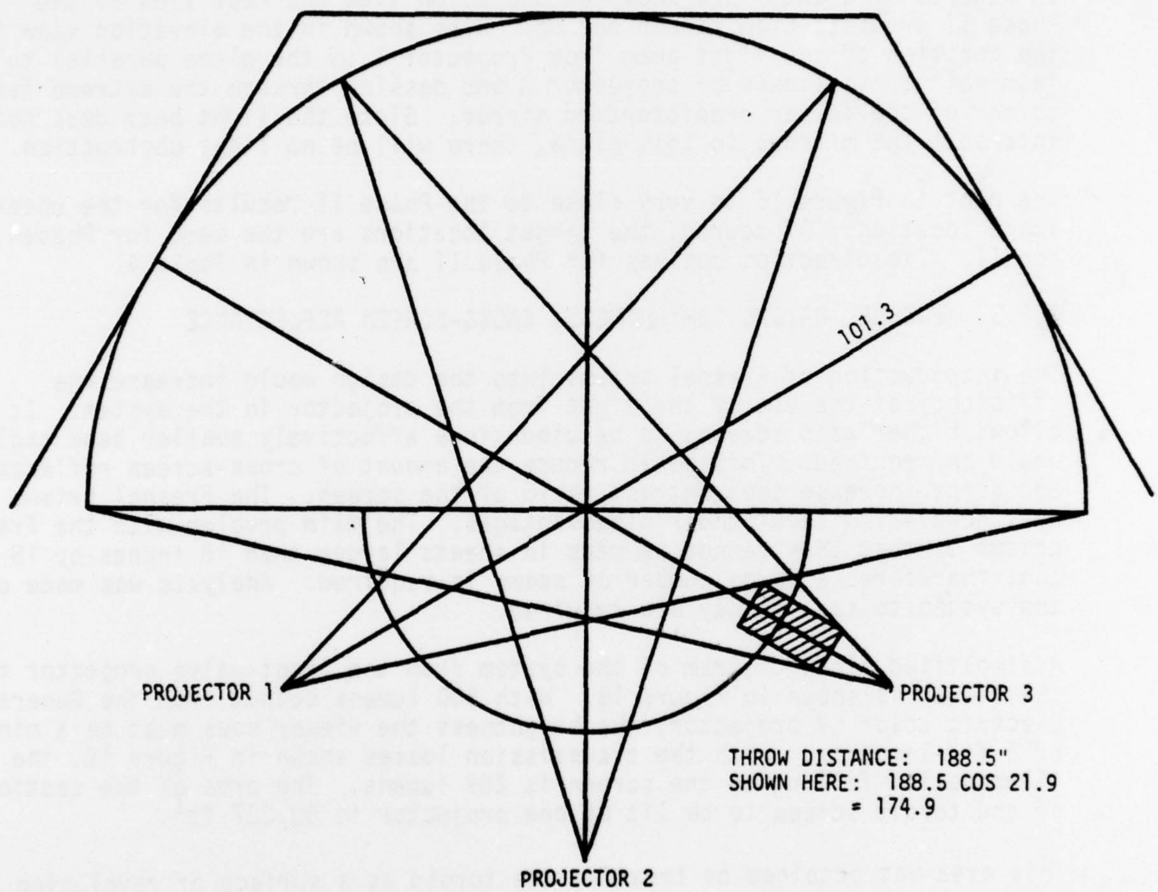

Figure 16. Plan View of Phase II Design

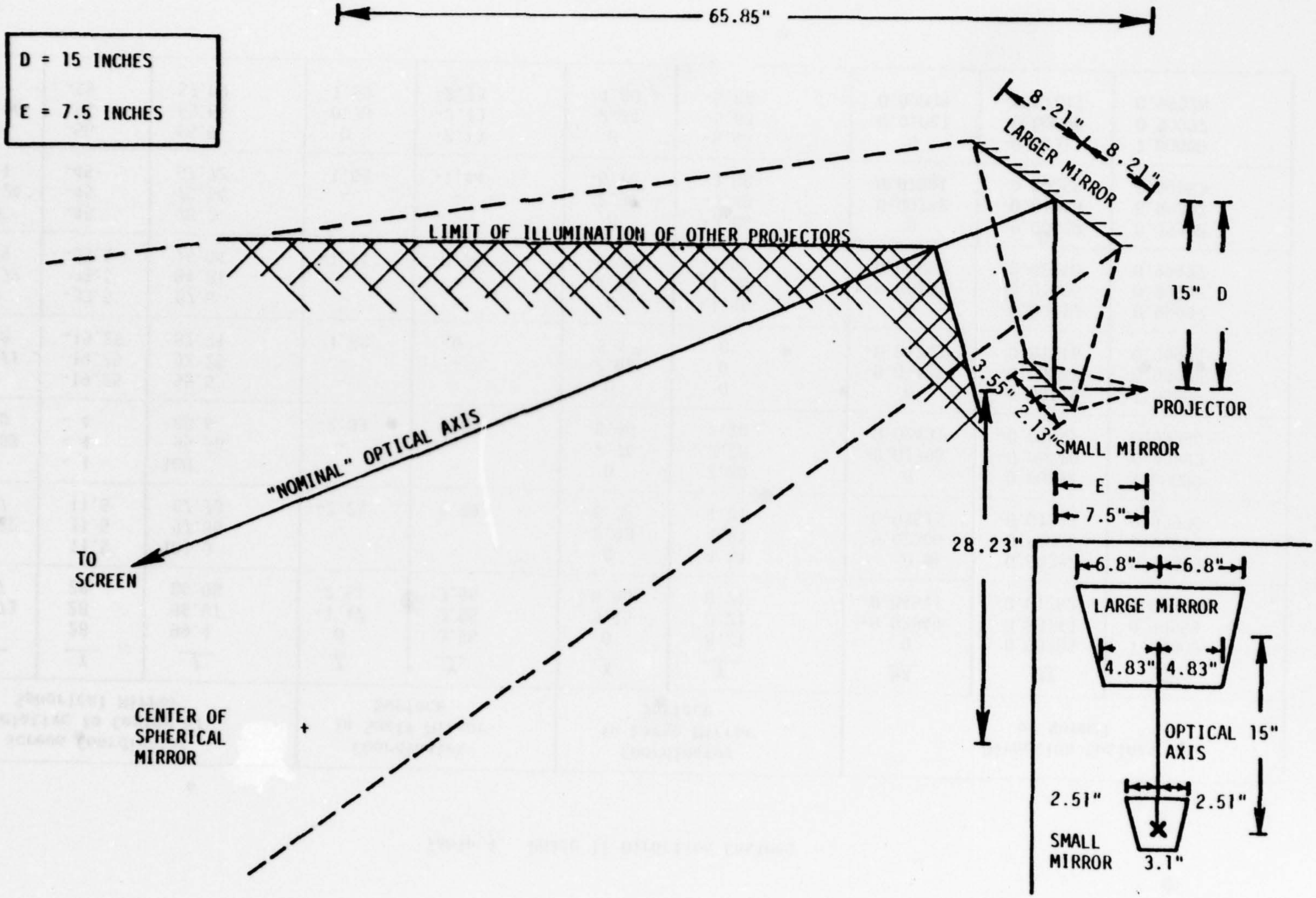

Figure 17a. Phase II Design

Figure 17b. Rear View

Table 4. Phase II Direction Cosines

Screen Coordinates Relative to Center of Spherical Mirror			Coordinates in Small Mirror Surface		Coordinates in Large Mirror Surface		Direction Cosines of Normal		
X	Y	Z	X	Y	X	Y	NX	NY	NZ
0	28	99.4	0	3.55	0	8.21	0	0.00285	1.00000
-25.73	28	96.01	-1.17	3.55	-3.15	8.21	-0.02849	-0.00144	0.99959
-49.7	28	86.08	-2.51	3.55	-6.80	8.21	-0.04511	-0.01262	0.99890
0	11.5	101.3	-	-	0	4.81	0	0.00382	0.99999
-26.22	11.5	97.85	-	-	-2.93	4.81	-0.02300	-0.00065	0.99974
-50.7	11.5	87.73	-2.23	1.99	-6.32	4.81	-0.03515	-0.01277	0.99930
0	- 4	100	-	-	0	2.20	0	0.00274	1.00000
-25.88	- 4	95.59	-	-	-2.76	2.20	-0.01796	-0.00280	0.99983
-50.0	- 4	86.6	-2.03	0.88	-5.96	2.20	-0.02431	-0.01442	0.99960
0	-19.25	95.5	-	-	0	0	0	-0.00179	1.00000
-24.71	-19.25	92.25	-	-	-2.62	0	-0.01125	-0.00632	0.99992
-47.8	-19.25	82.71	-1.88	0	-5.6	0	-0.01242	-0.01916	0.99974
0	-33.5	87.8	-	-	0	-1.98	0	-0.00713	0.99997
-27.72	-33.5	84.81	-	-	-2.49	-1.98	-0.00434	-0.01155	0.99992
-43.9	-33.5	76.04	-1.74	-0.76	-5.36	-1.98	0.00652	-0.02210	0.99973
0	-45	78.2	-	-	0	-3.88	0	-0.00639	0.99998
-20.24	-45	75.54	-	-	-2.37	-3.88	0.00252	-0.01059	0.99994
-39.1	-45	67.72	-1.63	-1.44	-5.10	-3.88	-0.01501	-0.00268	0.99963
0	-55	65.9	0	-2.13	0	-5.83	0	-0.00311	1.00000
-17.06	-55	63.65	-0.70	-2.13	-2.24	-5.83	0.01021	-0.00696	0.99992
-33	-55	57.07	-1.50	-2.13	-4.83	-5.83	0.03008	-0.01811	0.99938

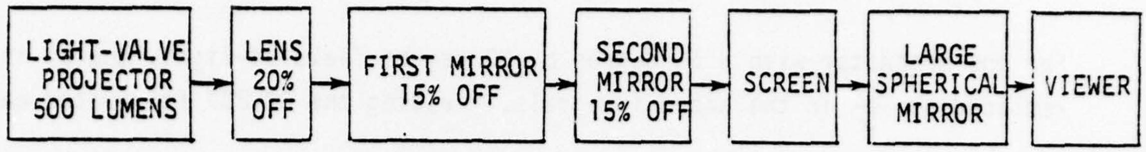

Figure 18. Block Diagram of the Optical System With Transmission Losses Specified At Each Stage

The integral given above reduces to

$$2\pi\int_{x=a}^{x=b}\left(r+\frac{kr}{\sqrt{r^2-x^2}}\right)dx$$

$$= 2\pi r\,(b-a) + 2\pi kr\sin^{-1}\left(\frac{b}{r}\right) - 2\pi kr\sin^{-1}\left(\frac{a}{r}\right)$$, where $r = 78.2363$,

$k = 23.1$, $b = 17.5$, and $a = -65.5$. See Figure 19.

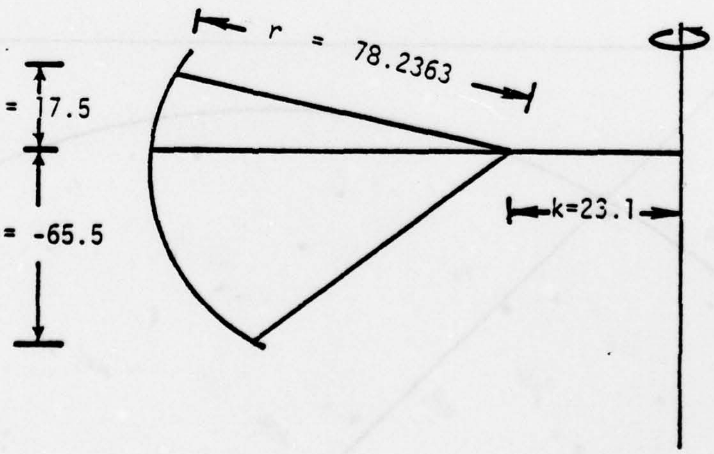

Figure 19. Cross-Section of Toroid

For one projector with a 60 degree by 60 degree field-of-light, the 2π is replaced by $\frac{\pi}{3}$ in the above integrals, yielding the 63.227 ft^2 quoted earlier.

We see that there are 4.57 lumens per square foot on the average. The screen must have enough gain to overcome the loss due to the spherical mirror, which is on the order of 15 percent. Therefore, we must have a gain greater than G given by (4.57) (G) (0.85) = 5, i.e., $G \geq 1.29$ at the appropriate bend angle. In Figure 4, the bend angles are seen to vary from 28 degrees to 38 degrees. Hence the screen must have a gain of 1.29 at 38 degrees. If special highly reflective mirrors could be used for the small projection mirrors, one can assume a transmission of 0.96 for each of these. This would require a screen gain of 1.01 at 38 degrees. In figure 9.7 of the book Display System Engineering by H.R. Luxenberg and Rudolph L. Kuehn, 1968, p. 296, the gains of several screens are shown. Only one out of the five shown have a gain greater than or equal to one at a 28 degrees bend angle and none have a gain nearly that large for a 38 degrees bend angle.

The contrast ratio for this material is computed by the following formula:

$$\text{C.R.} = \frac{\text{Light received at B from dA}}{\text{Light received at dA}}$$

where dA is lit by the projector as shown in Figure 20.

Figure 20. Cross-Screen Reflectance

The illumination per unit area at point B is given by the following formula:

$$I_B = \frac{I_{dA}}{2\pi R^2} \cdot R_{f_1} \cdot \cos\left(\phi_{dA}\right) \cdot \cos\left(\phi_B\right) \cdot (\text{Area lit at A})$$

where I_{da} and I_b are the illuminations of dA and B, respectively, R is the distance from dA to B, R_{f1} is the reflection factor and will be taken to be gain at the angle between the reflection vector at dA and the vector from dA to B, cos ϕ_{dA} and cos ϕ_B are the angles between the normals to these surfaces and the vector joining them, and the area lit at A is taken to be a 20 degrees by 20 degrees field-of-view as seen from the viewer, which is taken to be one-ninth the total area of the 60 degrees by 60 degrees field-of-view, i.e., about 7.025 ft^2. The gain angle, ϕ_{da}, and ϕ_{db} are taken to be 30 degrees for the example shown in Figure 21 and the distance from dA to B is 12 feet.

Then

$$\frac{I_B}{I_A} = \frac{(0.9)\ (0.866)\ (0.866)\ 7.025}{2\pi\ (12)^2} = 0.0052$$

Hence we have a 190 to 1 contrast ratio.

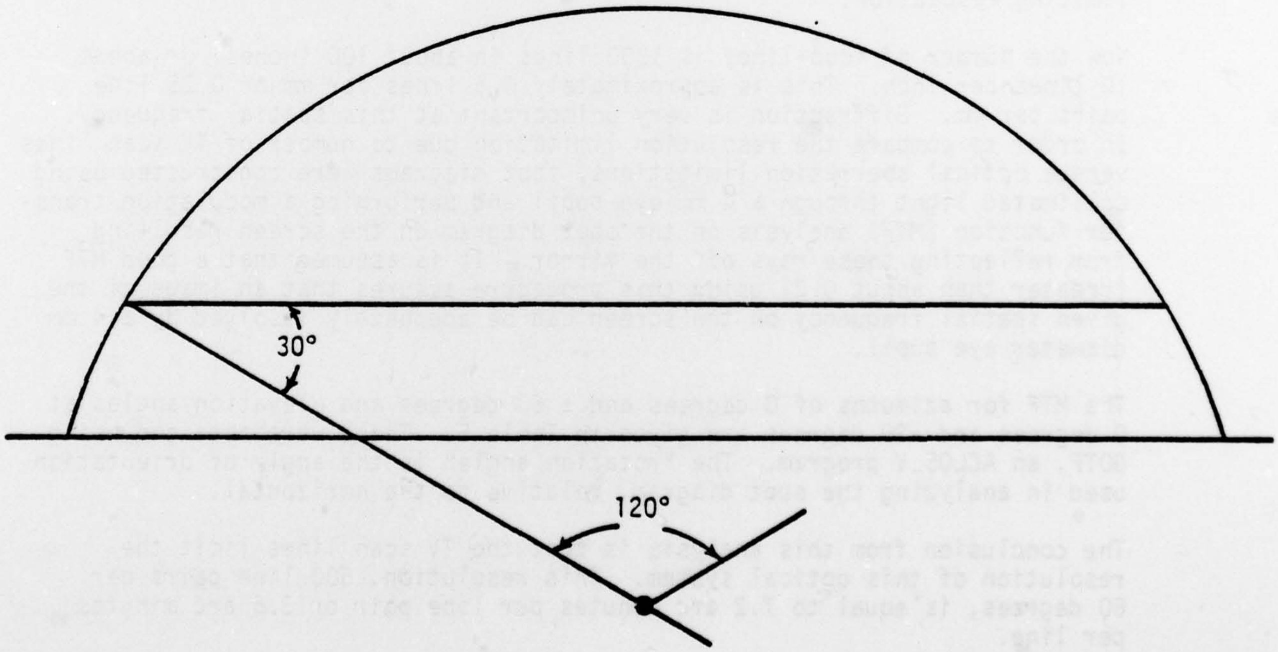

Figure 21. Plan View for Contrast Ratio Analysis

In conclusion, the system with 500 lumens output from the projector is not able to produce the required 5 ft-lamberts of brightness without the Fresnel prisms, but the contrast ratio is quite good.

Of interest at this point is a high brightness color light valve projector with an output of 2700 lumens developed by Sodern in France. This projector has 625 scan lines and the physical size is large. Sodern is receptive to the possibility of repackaging the projector for simulation applications and increasing the resolution. A verbal quote received by General Electric on the price for a single unit is $150,000 with a 9 month delivery. With this projector, suitably modified to meet the other requirements of this system, the 5 ft-lamberts could be obtained without the Fresnel prisms.

2.1.6 RESOLUTION

The resolution of this system can theoretically be limited by three things: the diffraction limit, the optical aberration limitations of the system, and the number of TV scan lines.

The theoretical frequency for diffration is given by the following:

$$\# \text{ line pairs per mm} = \frac{1800}{f\#}$$

If the eye pupil is assumed to have a diameter of 4 mm, then the f# is about 450 for this system, implying a limit of 4 line pairs per millimeter limiting resolution.

Now the number of scan lines is 1000 lines in about 100 inches, or about 10 lines per inch. This is approximately 0.5 lines per mm or 0.25 line pairs per mm. Diffraction is very unimportant at this spatial frequency. In order to compare the resolution limitation due to number of TV scan lines versus optical aberration limitations, spot diagrams were constructed using collimated light through a 4 mm eye pupil and performing a modulation transfer function (MTF) analysis on the spot diagram on the screen resulting from reflecting these rays off the mirror. It is assumed that a good MTF (greater than about 0.2) using this procedure assures that an image of the given spatial frequency on the screen can be adequately resolved by a 4 mm diameter eye pupil.

The MTF for azimuths of 0 degrees and ± 60 degrees and elevation angles at 0 degrees and -30 degrees are given in Table 5. These were obtained using GOTF, an ACLOS V program. The "rotation angle" is the angle of orientation used in analyzing the spot diagram, relative to the horizontal.

The conclusion from this analysis is that the TV scan lines limit the resolution of this optical system. This resolution, 500 line pairs per 60 degrees, is equal to 7.2 arc minutes per line pair or 3.6 arc minutes per line.

Table 5. MTF Results for Comparison of TV Scan-Line Limitations Versus Optical System Limitations on Resolution

	MTF — ELEVATION ANGLE 0°					
	SPATIAL FREQUENCY 0.25			0.50		
	Rotation Angle	0	45	90	0	45	90
MODULUS	AZ = -60	0.988	0.945	0.836	0.954	0.792	0.451
	AZ = 0	0.984	0.853	0.817	0.938	0.500	0.402
	AZ = 60	0.885	0.520	0.550	0.593	0.085	0.062
PHASE	AZ = -60	-0.01	0.03	0.05	-0.03	0.06	0.01
	AZ = 0	0.02	0.05	0.06	0.04	0.03	-0.02
	AZ = 60	0.05	0.04	0.05	0.06	-178.13	-177.53

	MTF — ELEVATION ANGLE -30°					
	SPATIAL FREQUENCY 0.25			0.50		
	Rotation Angle	0	45	90	0	45	90
MODULUS	AZ = -60	0.999	0.999	0.993	0.994	0.995	0.973
	AZ = 0	0.998	0.990	0.991	0.990	0.960	0.965
	AZ = +60	0.893	0.729	0.811	0.615	0.187	0.379
PHASE	AZ = -60	-0.01	0.00	0.01	-0.01	0.01	0.02
	AZ = 0	0.01	0.01	0.01	0.01	0.03	0.02
	AZ = +60	0.04	0.05	+0.05	0.04	-0.24	-0.01

2.1.7 MASKING LENS

A lens system will need to be placed in front of the light valve projector for both Phases I and II in order to mask the image to an exact 60 degree by 60 degree image as seen by the viewer. This masking should be done on an intermediate image format inside the lens system. For Phase I, this could be included with the derotation prism. Details of this lens design are beyond the scope of this study.

2.2 MATERIALS AND CONSTRUCTION TECHNIQUE

This section will include some information on mirror construction methods, screen configurations and construction methods, laboratory investigations into screen characteristics, and predistortion mirrors.

2.2.1 MIRROR CONSTRUCTION

The main collimating mirror is spherical and has a radius of 14 feet. See Figure 4. It wraps nearly 180 degrees around in a horizontal plane and extends in height from about 20 inches below to 140 inches below its center of curvature. Its area is very nearly 400 feet square.

There are several methods that might be used in constructing the mirror. There is an epoxy replicating method that is used by Talbert Reflectors of Oakland, California. The mirror is formed by applying a separating layer, an epoxy layer, an aluminum honeycomb core, and a final epoxy and fiberglass backing to a master convex spherical mold. Surface accuracies of 0.5 arc minutes per foot slope error have been achieved. The process lends itself to large mirror making (up to 12.5 feet diagonal have been worked). For this particular application Talbert recommends between 24 and 36 trapezoidal segments, 3 to 4 rows across the 12 foot mirror height and 8 or 9 around the circumference. The actual number and size of segments would be dictated by the size of optical coating chamber available at the time an order is placed. The method has the advantage that each segment can be considered a structural unit in itself without external rigging. A further advantage is the weight of 25-40 pounds per segment. The gap between adjoining elements can be made as small as 2 arc minutes. A budgetary estimate of the cost is $512,640 with a 12 month delivery schedule for all segments.

A second method for making the mirror is that of electroformed nickel. In this process a layer of nickel is deposited by electrodeposition on a master mold. This layer is about 0.032 inches thick. The surface is backed by another material, which was undefined at the time of the discussion, to add rigidity and allow for incorporating mounting brackets. The segment is aluminized on the nickel surface. The entire array of mirrors would be supported by structural members. Optical Radiation Corporation of Azusa, California, has suggested using individual segments, about 4 feet by 4 feet, to build up the complete mirror. This would require about 30 segments. Budgetary cost for the tooling is $81,020 and for each mirror segment $2,900 bringing total cost to $168,020. This does not include the cost of the backing material. Delivery would require 5 months start-up with 2 mirror segments per week thereafter.

A third possible method is that of diamond-turning. The approach is simply that of computer-controlled diamond-cutting of the required surface slope. The largest diamond-turning machine in the United States is at the Department of Energy Research Laboratory at Oak Ridge, Tennessee. This facility is operated by Union Carbide Nuclear Division. The machine has the following maximum capacities:

Turning Diameter	80 inches
Curve-Generating Travel	24 inches
Continuous Cut	60 inches

The machine is tape-controlled to cut any shape. Best finish obtained is 2 μinches peak to valley. The machine is completely scheduled until the end of 1978. Even then authority to use the facility would have to come from NADC (Form 614A). Quotas would require scheduling information so no further inquiries were made. The process evidently offers some promise of success and might be considered as a candidate method.

A final method is that of complete plastic construction. The mirror segments are ground and polished acrylic with a backing of ribbing of the same material. The polished surface is aluminized with a relatively durable coating (rubbing test allowed but not Scotch tape snapping). Applied Products in Horsham, Pennsylvania, state that they can make segments up to a maximum of 4 feet square. This would require about 30 segments. Budgetary cost, including aluminizing would be $6000/segment or $180,000 total. Delivery could be made at the rate of 1 per week, or in the neighborhood of 30 weeks for the total job. The product weighs in the vicinity of 200 pounds per segment and would have an accuracy of 4-6 arc minutes.

2.2.2 SCREEN CONSTRUCTION

The rear projection screen is toroidal in shape with a radius of 78.24 inches in the vertical plane and 101.34 inches in the horizontal plane. See Figure 4. It has a full sweep of 180 degrees horizontally and a height of 28 inches above and 55 inches below the mirror center of curvature. The area is 189.7 feet square.

Figure 4 shows one of the special requirements of the screen. The upper limit of the field has a 28 degree bend angle downward which increases to 38 degrees downward at the lower limit. This suggests either that the screen gain be very uniform over a wide range of bend angles or that special methods be used to bend the peak of the intensity lobe to a direction within the range of 28-38 degrees downward. The latter has the advantage of better light efficiency and, therefore, produces a brighter display for the same input.

A method for producing the redirected intensity lobe is that of using "Fresnel-lens" type grooves across the screen which act as vertical arrays of small identical prism elements. Figure 22 shows the concept. One side, in this illustration the inside concave side of the screen, is the diffusing surface with a specific gain and intensity lobe. The other side of the screen has the "Fresnel-prism" surface. As Figure 22 shows the intensity lobe is redirected so that its maximum is in the desired direction. A later section will describe some experimental work that was done in the laboratory on this concept.

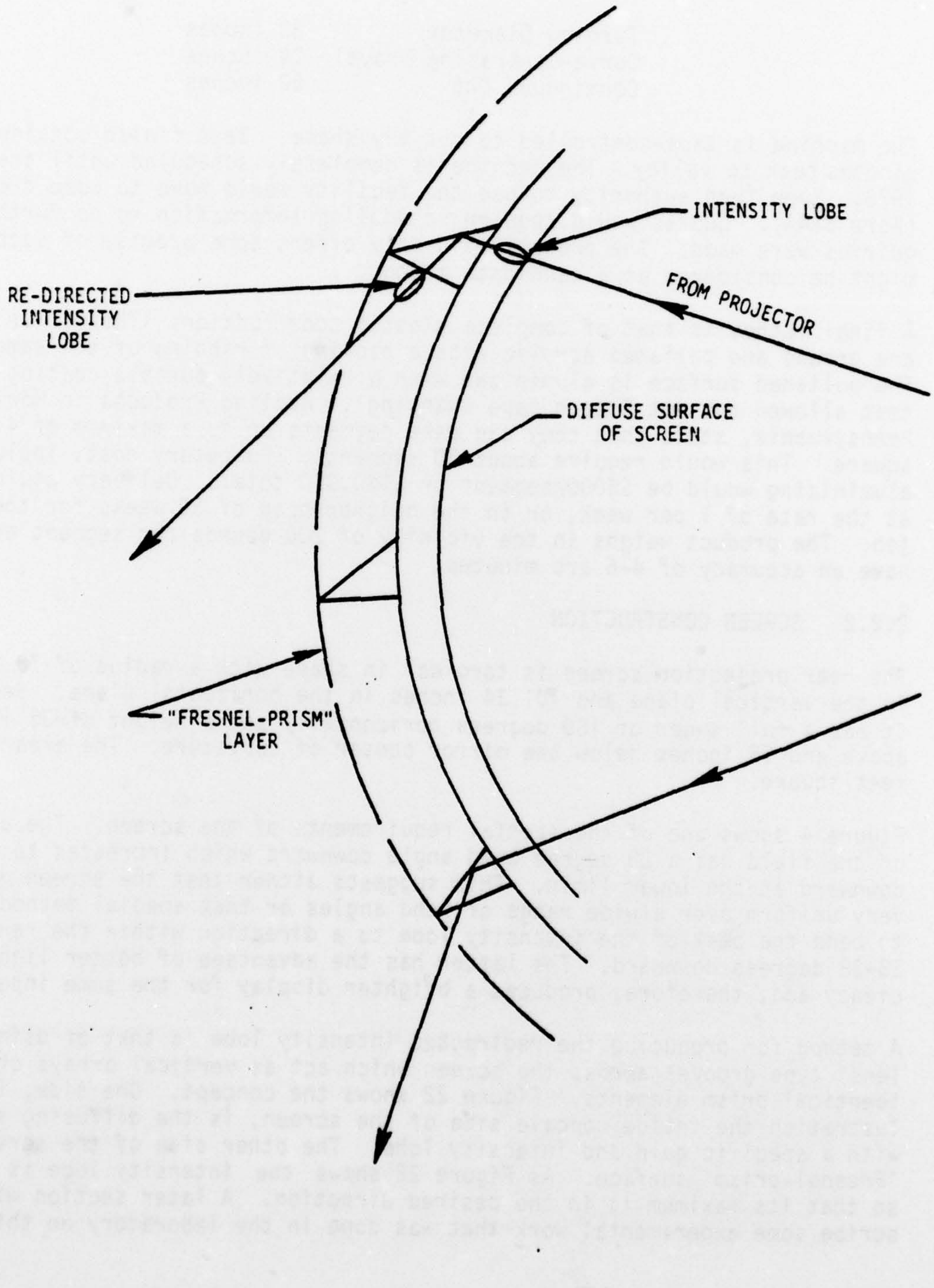

Figure 22. "Fresnel-Prism" Concept

The screen can conceivably be constructed by three vendors. The substrate has been postulated as stretched transparent acrylic, a material used in aircraft canopies. One vendor forms the material with heat and pressure to a mold with the desired shape. A second vendor applies the diffusing layer. If a plain diffusing layer is used it is preferably applied, from the manufacturer's standpoint, on the convex side of the molded substrate. If a "Fresnel-prism" layer is applied the diffusing coating is preferably applied on the concave side of the substrate as shown in Figure 22. In either case the diffusing coating is applied on the side of the substrate on which the abutted elements of the total screen are made flush while bonding them together. The screen substrate must be made up of multiple individual formed elements which vary slightly in thickness. If a "Fresnel-prism" layer is required a third vendor will produce individual segments that will be bonded to the convex side of the substrate. The individual "Fresnel-prism" segments will have dimensions of approximately 18 inches by 18 inches.

Swedlow, Inc. of Garden Grove, California, has given a quote on forming the substrate using stretched acrylic meeting MIL-P-25690A. They recommend using 8 segments. Their approach would be to form the curves on 8 oversize segments, send those segments to the coating vendor, then have them returned for trimming and assembling. Their budgetary cost is $60,000 with delivery of the first segment 10 weeks after receipt of the order. The remaining segments would be produced rapidly after that. The thickness tolerance would be 10 percent or 0.25 inch nominal thickness.

Polacoat, Inc. of Cincinnati, Ohio, feels that the curved screen segments can be coated. They prefer the convex side as stated earlier but may have to go to the concave side if the "Fresnel-prism" idea is used. The gain of the "Fresnel-prism" screen, assuming the use of a GE Model 4PJ5150B light valve projector, should be in the region 1.3 to 2.0. A screen with pure diffusion and no "Fresnel-prism" enhancement would produce a final brightness, to the observer of approximately 2.7 footlamberts which is unacceptable. Polacoat states that it is more difficult, although feasible, to coat the curved substrate segments. They would prefer coating flat segments and returning them to Swedlow providing that the forming process does not exceed a temperature of 300°F. No cost or delivery information was obtained but it is expected to be relatively low.

Laboratory experimentation with Fresnel-lens segments has shown that the prism elements should be used to produce internal reflection rather than refraction. The latter is the operational mode of Fresnel lenses, but it produces unacceptable color fringes for this application. Figure 23 shows the desired path of a ray through the rear projection screen and includes the total reflection path through the prism. The prism material was assumed to be methyl methacrylate (acrylic, lucite, plexiglass) which has an index of $M_D = 1.491$. With this material the critical angle for total internal reflection is 42.12 degrees. The incident angle in this application is 63.6 degrees as shown in Figure 23. It is sufficiently greater than the critical angle to allow a conical spread of rays around the ray shown and thus permit liberal viewing freedom.

Fresnel Optics, Inc. of Rochester, New York, and Optical Sciences Group of San Rafael, California, were approached for information on the feasibility of

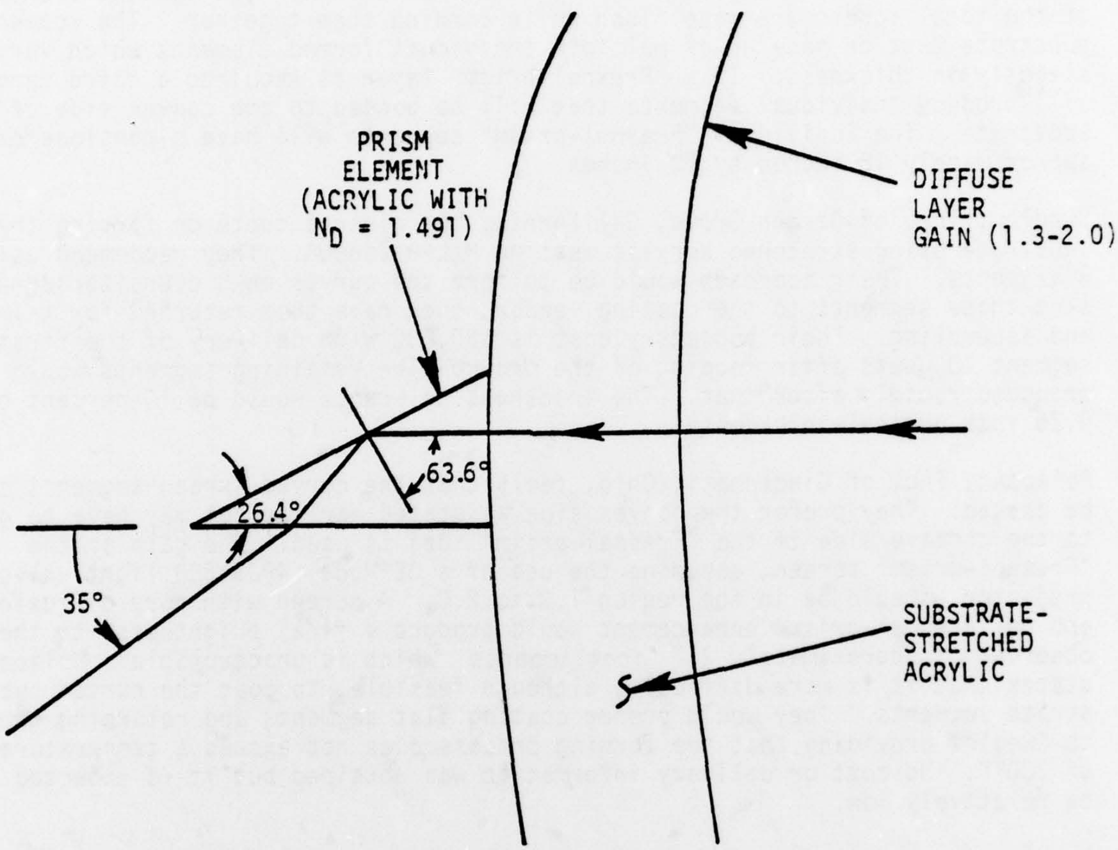

Figure 23. Cross-Section of Toroidal Rear-Projection Screen with "Fresnel-Prism" Layer Showing Typical Ray Path

the approach. Optical Sciences Group was not ready to quote without drawings, which were submitted, but because of press of time did not materialize. Fresnel Optics felt that the "Fresnel-prism" master could be made in a maximum 18 inch by 18 inch size. Approximate costs would be $4200 for the master mold and $24 each for the segments. There would be about 85-100 segments needed for a maximum cost of $2400. Total cost would be $66[illegible].

The basic plan for manufacturing the toroidal rear-projection screen would, in summary, involve the following steps:

a. Form oversize stretched acrylic substrate segments to curvature.

b. Deliver substrate segments to coating manufacturer. Coating will be done on convex side for pure diffusor screen, on concave side for "Fresnel-prism" type screen.

c. Return coated segments to substrate-forming vendor for trimming and assembly.

d. While these steps are being taken the "Fresnel-prism" segment vendor will have been manufacturing those segments. The segments will be bonded to the convex surface of the screen. The purveyor and location of this bonding service are not defined at this time.

2.2.3 LABORATORY INVESTIGATION INTO SCREEN CHARACTERISTICS

A laboratory setup was made as shown in Figure 24. A 35mm projector was arranged to project a 1 inch diameter circular patch of white light from a distance of several feet to provide a narrow angle input beam. The rotary table for the test specimen mounted the diffuse sample target plus a segment of the outer portion of a Fresnel lens. A Pritchard photometer was connected to another rotary table that was coaxial with the one mentioned above. It permitted the photometer to be rotated to any desired off-axis angle.

The illumination at the sample position was first measured with an EG&G photometer. That value was used to calculate all screen gains. The sample diffusors were then matched up, in turn, with and without the Fresnel-lens segment to measure, essentially, the brightness in the 60 degree off-axis relative to the on-axis direction. Figure 23 shows that the Fresnel-lens cross section is such that total internal reflection occurs at 60 degrees off-axis. That cross section, however, is not ideal for this application because its shape and angle are wrong. The cross section of Figure 23 is correct. Table 6 gives the results.

What this table shows is the great benefit to be obtained by using the "Fresnel-prism" concept for the higher gain screen. For example, the flashed opal, with a gain of 0.6, shows very little change regardless of the screen modifications. However, for a higher gain screen such as the Polacoat LS60PL the enhancement of the brightness with the "Fresnel-prism" supplement is 2.34 to 0.20. The 2.34 gain at 60 degrees is over 70 percent of the on-axis gain.

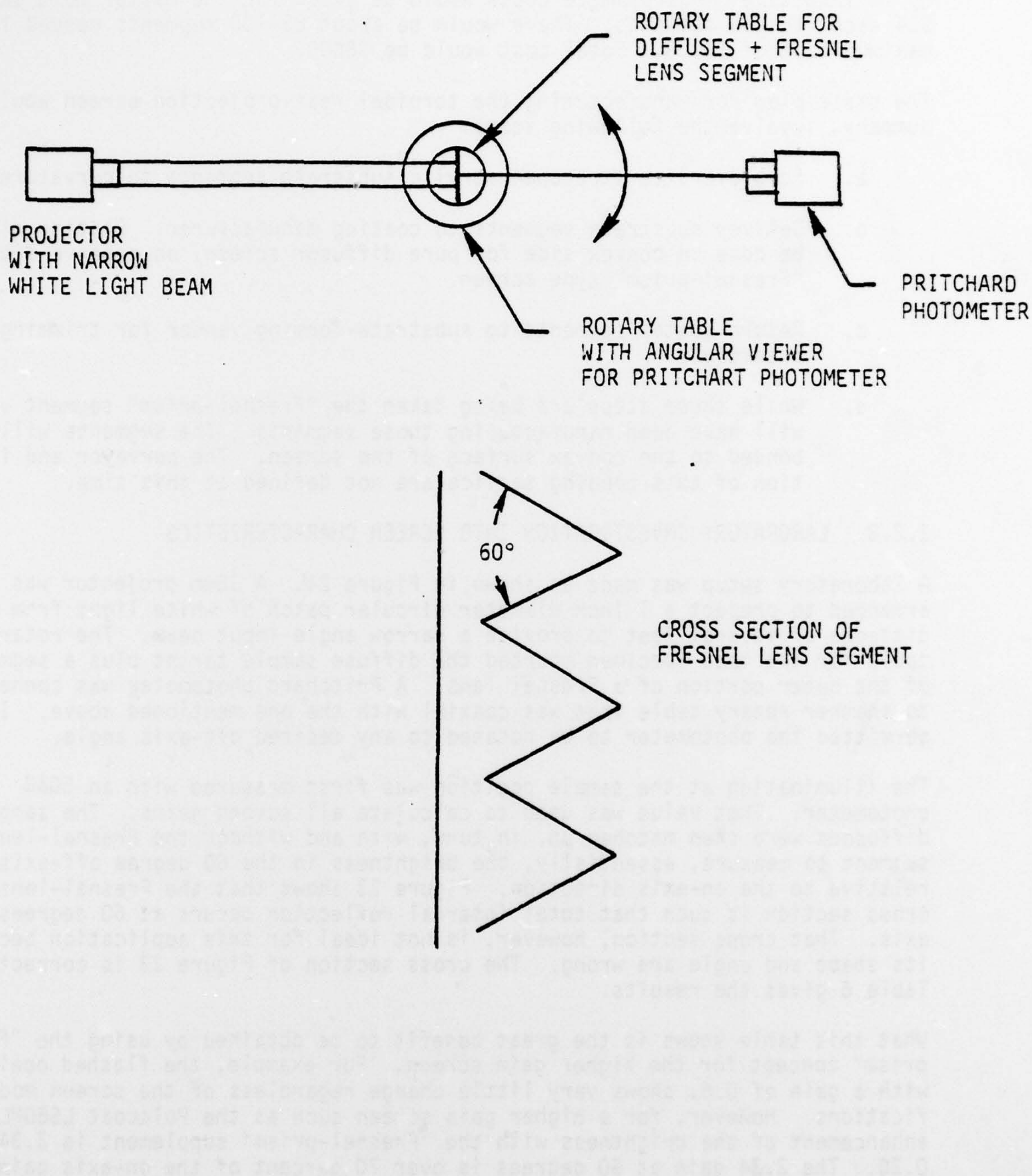

Figure 24. Laboratory Setup For Measurement of Diffuse Screen - "Fresnel-Prism" Characteristics

Table 6. Results Of Laboratory Experimentation On Diffusor And "Fresnel-Prism" Groups

Illumination at Sample = 1166 lumens/foot squared

$$\text{Screen Gain} = \frac{\text{Brightness}}{1166}$$

	Brightness (Footlamberts)		
	No "Fresnel Prism"		"Fresnel Prism"
Screen Type	0°	60°	60°
Flashed Opal	690	618	700
Gain =	0.59	0.53	0.60
Polacoat Lens Screen LS60PL	3835	235	2725
Gain =	3.29	0.20	2.34
Chroma Screen CS-140	5675	251	3635
Gain =	4.87	0.22	3.12
Ground Glass (Plastic Substrate)	26300	142	11330
Gain =	22.6	0.12	9.72

During this testing visual observations were also made that very little light was scattered by the "Fresnel-prism" element. Finally, to dispel any doubts about the effect of the prisms on image quality due to misalignment of the "Fresnel-prism" segments, two small elements were moved side by side near the image plane while observing the change in the image. The observer was unable to see any changes regardless of the position one segment was positioned in relation to the others. Additionally, the prism strips will hardly compromise image quality provided that the ratio of prism rows to each television line is about 10 to 1.

This requires about 50 grooves/inch on the "Fresnel-prism" segment. A finer structure like 100 or 200 grooves/inch will also contribute to greater image degradation.

2.2.4 PREDISTORTION MIRRORS

Tables 3 and 4 list the modifications that must be made to the second folding mirror (nearest the screen) for Phases I and II, respectively. Specifically, the tables list the changed direction of the normals for each of those initially flat surfaces.

To determine an equation for the surface a function, which does not assume rotational symmetry, is formulated. Such an equation would be:

$$z = g(x,y)$$

where Z is the departure of the surface from a flat reference level and

$$g(x,y) = d_{O_1}(d_{O_6}x^2 + Y^2) + d_{O_2}(d_{O_7}x^2 + y^2)^2 \qquad (1)$$

$$+ d_{O_3}(d_{O_8}x^2 + y^2)^3 + d_{O_4}(d_{O_9}x^2 + y^2)^4$$

$$+ \ldots$$

If the surface equation is put in the form,

$$o = z - g(x,y)$$

the normal vectors take on the form,

$$\vec{M} = \vec{c}\,\frac{\partial g}{\partial x} + \vec{\alpha}\,\frac{\partial g}{\partial y} - \vec{k}$$

The partial derivatives are simply direction numbers of the normal vector and are proportional to values in Table 3 or Table 4. These tabular values are equated to the expressions for $\partial g/\partial x$ and $\partial g/\partial y$ from equation (1) above. The corresponding (x,y) coordinates for the locations of the appropriate normals are also entered into the expressions. This leaves a group of equations in which the only unknowns are the coefficients d_{O_1}, d_{O_2}, d_{O_3}, etc. The solution of as many equations as there are coefficients desired will result in the generation of a surface equation to any degree of precision. That equation will supply the z-heights above flatness that will be needed by the surface manufacturer.

Special surfaces, such as these, can be handled by vendors with computer-driven curve generating equipment. The z-heights are the inputs to the computers. The need for surfaces which go beyond even the rotationally-symmetric aspheric types is becoming more and more prevalent. They are referred to as "contour-spline functions" in the optical program, ACCOS V. Additionally, Figure 15 shows that the surfaces are very smooth and gently-varying and could conceivably be made by simple manual figuring by an experienced optician.

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